# Provincial-Level Projection of the Current Mountain Pine Beetle Outbreak:

## An
## Overview of the Model (BCMPB v2)
## and
## Results of Year 2 of the Project

*Supported by the*
*Mountain Pine Beetle Initiative of the Canadian Forest Service*
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The province of British Columbia contributed virtually all of the data that was used in the project.

We would also like to thank participants of the workshops for providing valuable guidance about beetles and forest management, and scenarios for the modeling exercise. See http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Workshop_Fall2003_Minutes.pdf, http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Workshop_Spring2004_Minutes.pdf, and http://www.for.gov.bc.ca/hre/bcmpb//BCMPB_Workshop_Spring2005_Minutes.pdf for a list of participants at the workshops.

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# BCMPB v2: Results of year 2 of the project

## 1.0 Executive Summary

The second version of BC Provincial-Level Mountain Pine Beetle Model (BCMPB v2) was developed as part of a two-year project to assess the impacts of mountain pine beetles (MPB), forest management, and interactions between these factors across the province. This report describes the model and the results of the second year of work. The results of the first year of work can be found at http://www.for.gov.bc.ca/hre/bcmpb/year1.htm. The MPB outbreak sub-model is driven by overview infestation maps from 1999 to 2004. The forest management sub-model uses inputs from the forest cover inventory and management information to simulate forestry activities within each timber supply area and tree farm license, including MPB management and salvage harvesting.

We project that the current outbreak will be at its worst in 2006. During that summer 90 million $m^3$ of merchantable pine on the timber harvesting landbase may be killed. Based on the behaviour of the outbreak to date we have no reason to expect that it will kill less than 80% of the pine volume. Nonetheless, there is uncertainty about when and how the infestation will end. We model the assumption that the infestation continues but kills less of each stand than we have observed and the assumption that the infestation ends abruptly at a point earlier than we project as a worst case. Those assumptions have significantly different implications on forest management. The work required to determine which of the assumptions is most likely should be undertaken immediately.

There is significant uncertainty about the length of time that beetle killed wood will be useable for any given product (its "shelf-life"). We modeled differences in shelf-life and found dramatic effects on the amount of timber volume that we will be unable to harvest in a timely manner (non-recovered losses). By 2016 pessimistic assumptions about shelf-life result in 500 million $m^3$ of non recovered losses whereas optimistic assumptions result in only 200 million $m^3$ of non-recovered losses. Work is currently underway to provide some better estimates of the biological and engineering/manufacturing aspects of shelf-life.

We examine the implications of various alternative harvest levels. Increasing harvest levels reduces non-recovered losses. However, the majority of the susceptible pine occurs in stands where it is mixed with non-pine species. Therefore, if we increase our salvage efforts we also increase our harvest of non-pine volume. For every cubic metre of non-recovered losses that are saved we also harvest 1.3 cubic metres of non-pine volume as an "incidental by-catch".

We observe that, if the volume harvested remains constant, the area harvested increases over the first 8 years of the projection and then decreases over the next 12 years. The reason is that volume per hectare harvested initially decreases as more of the dead pine becomes unusable, and then increases again as harvesting switches from salvage logging of dead pine to the harvesting of non-pine.

We will continue to refine the data and model over the coming year.

# 2.0 Introduction and Objectives

Mountain pine beetles (*Dendroctonus ponderosae* Hopkins MPB) are currently in the outbreak phase of the infestation cycle throughout much of their range in British Columbia. Adequate management of this provincial scale problem requires provincial scale knowledge. While we cannot hope to accurately predict the exact progression of the infestation, we can project a range of possibilities, given a variety of assumptions and uncertainties. Our hope is that these projections will help managers make more informed decisions about provincial and national level policies. Used appropriately, the results may also help guide actions at a management unit scale.

This project can be described by a series of key steps:

- consulting with potential users to develop and refine the scope and objectives;
- obtaining geographic, forest inventory, forest management and mountain pine beetle infestation data for the study area;
- analyzing the data to understand as much as possible about the course of the outbreak over the past six years;
- combining the results of our analysis with expert knowledge and results from more detailed fine-scale models to develop a provincial-scale projection model;
- projecting the outbreak forward given a range of management options and assumptions about beetles, and
- interpreting the projection results.

We investigated the course of the outbreak over a 20-year period, focusing mainly on the area affected and timber volumes killed by beetles, and the consequent effect on non-recovered losses and pine growing stock across the province. Our "reference scenario" does not include any infestation-stopping mechanisms such as severe winter weather events. We simply project the depletion of the mountain pine beetle's host (mature pine of all species). Therefore, the results of this project should be viewed as a worst-case scenario.

Our main goal this year was to examine the sensitivity of results about wood supply and non-recovered losses to various poorly defined model parameters. Last year our focus was on the efficacy of forest managers' aggressive attempts to slow the outbreak. We modeled their management strategy, known as "leading edge attack", given our current understanding of beetle biology and the observed behaviour of this outbreak. We found no evidence, virtually anywhere in the province, that the attempt to control the outbreak either slows its spread nor has any positive outcome with respect to the amount of live pine left on the landscape when the outbreak subsides. "Leading edge attack" may have had some success controlling previous outbreaks but the unprecedented size and aggressive nature of this outbreak appears to render it ineffective. However, there are hypotheses about beetle biology involving mechanisms that could slow or stop the outbreak, particularly at its periphery. If these hypotheses are correct some efforts at beetle control at the periphery of the outbreak may be warranted. A detailed discussion of assumptions and conclusions about beetle management can be found in the report from the first year of the project (http://www.for.gov.bc.ca/hre/bcmpb/year1.htm).

This year our efforts were focused on answering the following questions that were raised in the first annual reporting out workshop (http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Workshop_Spring2004_Summary.pdf):

- How much beetle-killed wood, and of what quality will likely be harvested by the "sawlog" (dimensioned lumber) industry?
- What will be the amount of non-recovered losses and volumes available for various alternative industries under a set of "reasonable" assumptions?
- How sensitive are results to assumptions about:
    1. the duration of the outbreak,
    2. assumptions about the shelf-life of beetle killed timber for any particular purpose, and
    3. specification of what constitutes a valid salvage block (percentage of pine and volume of dead pine)?
- What are the implications of increasing harvest levels in affected management units?

It is important to note that our forest management model is designed to mimic the actions of the "traditional" forest industry in British Columbia's interior. Importantly, in this context, the model seeks wood useable for dimensional lumber (sawlogs) and "chips" (pulp) are considered a by-product. We do not attempt to model the actions of the anticipated "alternative" forest industry that will be using the dead pine primarily as "chips" for a variety of purposes such as oriented strand board, paper pulp and fuel. It is impossible to define the specifications of this alternative industry until it begins to emerge. Therefore we only provide information about the amount, quality (time since death) and spatial distribution of timber volume that may be available for this industry.

The mountain pine beetle outbreak and our management response affect a wide range of forest values. We do not attempt to analyze the implications of these impacts, as we believe that this is best done by topic experts (e.g. economists, caribou biologists). To this end, in collaboration with interested users we have designed indicator files that can serve as input for further analysis of economic, social and/or ecological cost/benefits by interested topic experts.

# 3.0 Methods

## 3.1 Overall Landscape Model Design

The general design of BCMPB in terms of linkages between model state, landscape processes and output files is shown in Figure 1. The following description summarizes the structure, operation and data requirements of the model. More detailed descriptions of the management sub-model (including planning and harvesting) and the mountain pine beetle sub-model are provided Appendix 2 and Appendix 3 respectively. A detailed discussion of the input data is provided in Appendix 1.

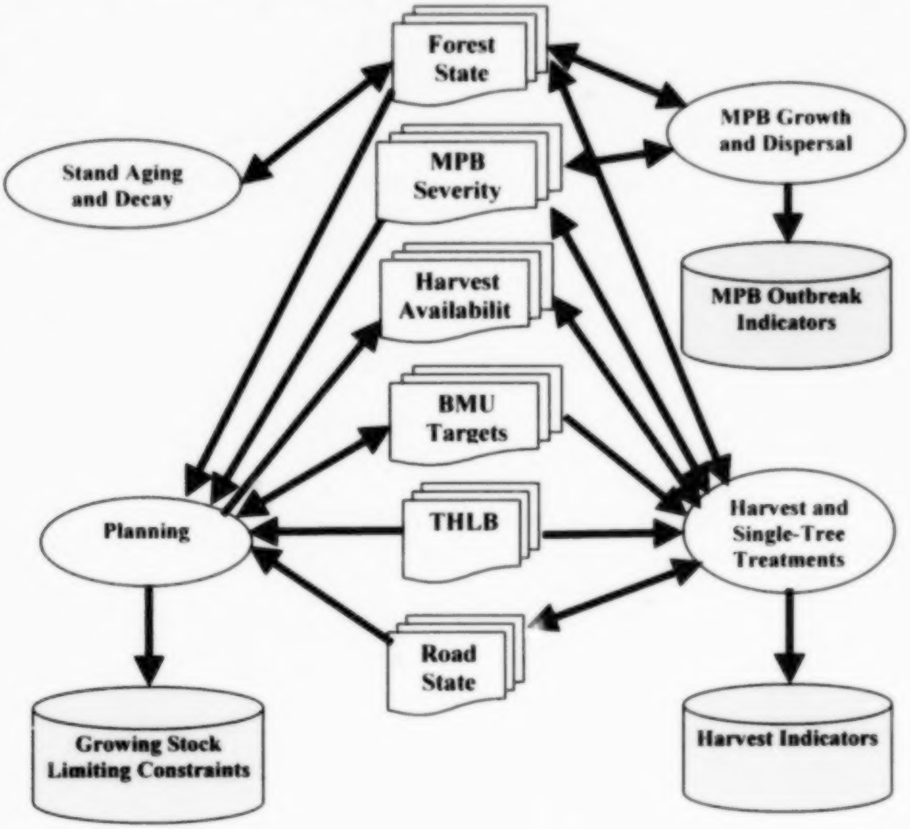
Forest State
MPB Growth and Dispersal
MPB Severity
Stand Aging and Decay
Harvest Availabilit
MPB Outbreak Indicators
BMU Targets
THLB
Planning
Harvest and Single-Tree Treatments
Road State
Growing Stock Limiting Constraints
Harvest Indicators

Figure 1. *Linkages between primary components of state (shown in the centre), model processes (shown in ovals) and output files (shown as grey drums).*

### 3.1.1 Model State Space

The following data layers comprise the model state space. Each spatial variable is represented by a grid of 16 hectare cells that are assumed to be homogenous with respect to the layer attributes.

Landscape structure: the landscape biogeographical context and the limits of the study area are defined with the following spatial variables:

(i) BEC: biogeoeclimatic classification by variant.
(ii) Elevation: elevation in metres

Forest State: the forest is represented by the following layers:

(iii) Age: age in years (projected to start year).
(iv) ITG: inventory type group (leading and secondary species).
(v) VolPerHa: standing volume/ha for trees greater than 12.5 cm dbh (as reported in the inventory database).
(vi) PineVolPerHa: standing volume/ha that is pine greater than 12.5 cm dbh(as reported in the inventory database).
(vii) Percent pine: Percentage of stand that is pine based on inventory (percentage of canopy, but also assumed to be percentage of volume).
(viii) Pine volume killed by beetles in each year since 1999, stored as a list in each cell to allow application of various decay functions (e.g. for sawlog and chip merchantability as described in the next section).
(ix) MPB Susceptibility: estimated according to the index developed by CFS (Shore and Safranyik, 1992), but lacking stand density.

Mountain Pine Beetle Severity State:

(x) State of attack in each cell: represented using broad classes similar to those in the provincial aerial overview data: based on the percent of pine in each cell that has been attacked: no mountain pine beetle (0% attack), endemic (<1% attack), low (1-10% attack), medium (10-20% attack) and severe (> 20% attack).
(xi) Cumulative percent of pine killed by beetles since 1999 using same classes as the above annual state.

Harvest Availability:

(xii) PotentialTreatmentType: the available forest is stratified into the type of treatment that would be applied if a harvest block were initiated at that cell. Valid treatments are discussed in a subsequent sub-section.

Timber harvesting landbase:

(xiii) THLB: the timber harvesting landbase is derived from the productive operable forests by using a netdown process that removes forest for various reasons, applied spatially. Individual cells are either completely within or outside the THLB. Most reasons for removal apply to entire cells (e.g. non-merchantable forest), but some may remove only portions of a cell (e.g. roads, riparian zones). In these latter cases, we chose whether to include or exclude a cell randomly using a probability equal to the proportion.

Management Zones:

(xiv) MgmtUnit: management unit (TSA or TFL)
(xv) LU: Landscape Units
(xvi) BMU: beetle management units and strategy type
(xvii) VQO: visual quality objective zones.

Management Parameters: A range of parameters and tables represent the harvesting regime, including:

(xviii) AAC (annual allowable cut): the "target" area to be harvested per year for each management unit. For TSAs this was obtained directly from the most recent Timber Supply Analysis reports. For TFLs the volume target was converted to an area based on average volumes per hectare. This may vary through time independently for each unit.
(xix) BMUStrategies: beetle management unit strategies described below.
(xx) Minimum harvest volume: generally 150 $m^3$ per ha except for salvage.
(xxi) Management constraints: described below
(xxii) Management preferences: described below

Roads:

(xxiii) DistanceToRoads: distance to existing roads in metres.

### 3.1.2 Shelf-Life of Beetle Killed Wood

We developed a conceptual shelf-life model based on data presented by the Vanderhoof IFPA (Thrower 2003) and numerous communications with domain experts, primarily district level staff within the BC Forest Service. Details of the implementation of the shelf-life model can be found in Appendix 4.

We define shelf life as "the length of time after death that a tree will be useable for a given product." Therefore, "shelf-life" is product specific and differs for sawlogs, OSB, pulp, bio fuels, woodpecker habitat, etc. A corollary of this concept is that the actual volume of timber in an MPB killed stand may remain the same for some significant length of time but will change in character as time progresses.

A narrative version of our conceptual model of shelf-life is:

- There is a relationship between time since death and applicable products for (stands of) pine trees killed by MPB.
- Beetle killed logs will be useable as sawlogs (dimensional lumber) during the winter and summer harvesting seasons immediately following their death.
- For (X) subsequent years they loose their bark and begin to deteriorate in quality (with some minor checking) but essentially the entire volume will continue to be useable as sawlogs.
- From (X) to (N) years, the volume that can be used as sawlogs will decline in a linear fashion to the point where none of it is useable for dimensional lumber.
- From (X) to (M) some portion of the volume, in addition to that useable as sawlogs, will be useable for "alternative purposes", for example, chips, biofuel, etc. The decline in the amount of total usable wood (from X to M) years) will occur in a linear fashion.
- (N) and (M) will vary depending on the biogeoclimatic subzone and will be shorter in wetter subzones than in drier subzones.

In order to implement this conceptual model we developed a process for grouping subzones into dry, moist and wet categories that would correspond to slow, moderate and fast degradation rates of timber quality. In general it is assumed that the rate at which standing fiber will degrade from sawlog to chips and then to unmerchantable bears some relationship to the moisture regime of the climate. Degradation is the result of two factors; checking and sap rot. Checking is assumed to be more severe and more rapid in moister climates because ring width is positively correlated with growing season moisture; narrow rings are denser and hence less susceptible to checking. In addition, it is believed that more checking may occur in moister climates because shrinkage may be more severe in wet wood, and because winter freeze-thaw cycles may be more pronounced. Sap rot is assumed to occur more rapidly in wetter climates (particularly growing season moisture) because moisture is an important determinant of the ability of those fungi to grow and reproduce.

The relationships described above are not well understood. For that reason we rely on a categorization of Biogeoclimatic Subzones into 3 groups; slow, moderate and rapid degradation rates. We use Biogeoclimatic Subzones rather than actual climatic maps because the Biogeoclimatic Subzones integrate a number of climatic variables and because forest practitioners are familiar with the zoning and can provide input and criticism based on local knowledge.

### 3.1.3 Mountain Pine Beetle Outbreak Model

The mountain pine beetle outbreak sub-model is a discrete state change model. In each year at each location the mountain pine beetle will be in one of five states.

The states are based on percent of pine trees in 16-ha cells that are currently (current severity) or cumulatively (cumulative severity) attacked:

1. NoMPB: 0% attack
2. Endemic: 0-1% attack
3. Low: 1-10% attack
4. Moderate: 10-20% attack
5. High: 20-100% attack

These classes are similar to those used in the overview survey, except we have added an additional class (Endemic) for very low attack levels, and decreased the threshold between moderate and high from 30% to 20%.

In each year of a simulation, the current mountain pine beetle state in each cell may remain the same, or change to more or less severe states. The probability of a given beetle state arising depends on the previous year's state, the cumulative amount of kill by beetles, host conditions in the cell, external mountain pine beetle pressure, and management effects. The state-to-state transition matrix is parameterized using observed transition probabilities in the overview data from 1999 to 2004.

Locations may be subject to local beetle dispersal pressure from nearby cells, long-distance pressure from cells many kilometers away, or no significant beetle pressure at all. There is some probability that infestations will arise "spontaneously" in areas not subject to significant dispersal pressure, presumably due to local increase in endemic beetle populations. We modify the beetle dispersal model from the landscape scale SELES-MPB model to estimate local beetle dispersal pressure across the province. There is little information available on the long-distance dispersal behaviour of beetles, so that portion of the model is based on the observed ability of proximity to existing outbreaks to explain infestation starts in the past overview data (i.e. we do not presuppose the effect that dispersal pressure will have on the probability of infestations arising).

The primary effect of mountain pine beetle attack is to shift living pine volume to standing dead volume (potentially salvageable wood). By killing trees, mountain pine beetles become indirectly visible to the management sub-model, thereby influencing the focus of harvest, single-tree treatments and BMU ratings.

### 3.1.4 Planning

This event performs an inventory analysis each time step. It tracks the amounts of forest old enough to harvest (merchantable), and determines which cells are available for harvest subject to road access and visual constraints. Note that the only forest cover constraint applied was for visual objectives (e.g. no rules for ungulate winter range, caribou, community watersheds, etc. were applied). For cells that are unavailable, this sub-model outputs information to determine which constraint(s) were responsible.

Cells that may potentially be harvested as salvage are also identified. A cell may be classified as "salvage" if three criteria are met:

(i) There is sufficient pine in the cell (percent pine is $\geq$ 50%)
(ii) There is sufficient beetle mortality in the cell (percent of the pine that is killed is > 50%)
(iii) There is sufficient merchantable sawlog volume in the standing dead wood and residual live wood (sawlog yield is $\geq 100m^3$).

The first criterion ensures that the amount of non-pine "by-catch" is limited. The second ensures that the stand has sufficient cumulative attack to be classified as a salvage cell and to limit "by-catch" of live pine. The last criterion ensures that the stand is still economic to harvest. Note that, since a cell may experience multiple years of attack, it is possible for a cell to meet both the requirements for "green" harvest and for salvage. In this case, the logging sub-model will select the classification with the highest preference, which depends on the type of the BMU in which the cell resides. The second key task of this sub-model is to establish beetle management unit (BMU) types. The possible types, and general management policies, are:

- *Monitor:* no beetles present; focus on green tree harvest
- *Suppression:* low to moderate mountain pine beetle; focus on reducing populations
- *Holding Action:* moderate to high mountain pine beetle; focus on reducing populations
- *Salvage:* high to very high mountain pine beetle, or post-outbreak collapse: focus on recovering standing dead volume.

For each BMU, an "outbreak level index" (*BMU rating)* was computed as follows:

$$(\text{Area with endemic mountain pine beetle}) + (\text{Area with mountain pine beetle} > \text{endemic})^2$$

This index roughly places an emphasis on non-endemic levels, but otherwise corresponds to increasing levels of MPB activity. BMUs are processed sequentially in increasing order of this index. If there are no detectable mountain pine beetles, then a BMU is assigned a *monitor* type. If the remaining single-tree budget (after reductions for previously processed BMUs) plus remaining AAC for the management unit is capable of addressing at least 80% of the "treatable" attack (all endemic cells plus non-endemic in the THLB), then a BMU is assigned a *suppression* type. Otherwise, if the remaining AAC for the management unit is capable of addressing at least 50% of the non-endemic in the THLB, then the BMU is assigned a *holding action* type. Finally, unassigned BMUs are assigned a *salvage* type. Once a BMU reaches a "salvage" type, it will remain there. See the following sub-models for details on how provincial single-tree budget, and management unit AAC is partitioned among BMUs, and how BMU types influence targeted harvesting.

### 3.1.5 Harvesting

This event performs forest harvesting simultaneously in each TSA/TFL in the province. Each management unit is processed independently, and so this sub-model can be described from the perspective of a single unit. In each unit, the target allowable annual cut (AAC), expressed using area, is harvested from the available cells.

Each year, the target area or volume AAC provides a "beetle management potential". How this is allocated across a unit depends on the BMU ratings, mountain pine beetle state, stand ages/volumes and salvage volumes, and is designed to capture the fundamentals of bark beetle management (MOF and BCE 1995). The available cells in the unit are stratified into groups based on BMU rating and mountain pine beetle outbreak state, and processed according to a priority order. Within each stratum, ordering is according to stand age or salvagable volume. The following describes the strata, from highest to lowest priority within a management unit for the reference scenario:

- Low and moderate mountain pine beetle in suppression BMUs: focuses harvesting on leading edge attack.
- Endemic and severe mountain pine beetle in suppression BMUs: focuses harvesting on other mountain pine beetle attack in suppression BMUs.
- Low and moderate mountain pine beetle in holding action BMUs: focuses harvesting on leading edge attack
- Severe mountain pine beetle in holding action BMUs: focuses harvesting on high populations
- Salvage in salvage BMUs: areas with adequate salvage (> $50m^3$/ha)
- Moderate and severe mountain pine beetle in salvage BMUs: focuses harvesting on areas likely to result in substantial salvage
- Salvage in other BMUs, and low and endemic mountain pine beetle in salvage BMUs: remaining "mop-up" classes
- Green harvest (no mountain pine beetle) in any BMU: regular green harvest

In cases of salvage, prioritization within the stratum will be according to amount of salvageable wood, while in all other cases prioritization will be according to age relative to estimated minimum harvest age. Both cases are influenced by road access. Hence in units with no mountain pine beetle (i.e. all BMU types will be *monitor*), all harvesting will be "green harvest", and hence according to "oldest-first, nearest to road". In management units with a mixture of BMU types, the actual allocation of harvesting will primarily focus on reducing populations, followed by salvage. In management units dominated by salvage BMU types, harvesting will be "highest salvage-volume first, nearest to road".

In some scenarios, the preference ordering above was modified. For example, to set up an "early switch to salvage" scenario, the preference for salvage blocks can be increased. As described in the previous section, if a cell is available for harvest according to both green criteria (i.e min. harvest age, VQO) and salvage criteria

(i.e. min. percent pine, min percent killed and min. volume yield), then the class with the highest preference will be applied.
The default cutblock size was 16-32ha (1-2 cells), based on an assessment of recent block sizes in different regions of the province, and on the bark beetle regulations. Note that smaller block sizes increases beetle management potential since harvest pattern can more closely track MPB attack pattern.

Where blocks are placed, volume (green and salvage) is recuperated, harvest indicators are updated, mountain pine beetle state is reset to "no mountain pine beetle" (i.e. the model assumes close to 100% efficacy), stand age is reset to 0, and visual targets are updated. All merchantable salvage (i.e. sawlog and chip salvage) is assumed to contribute towards the AAC. In addition, this sub-model explicitly connects cutblocks to the main road network by adding a link from the first cell harvested in a block to the nearest existing road. It then updates a map indicating the distance from each cell to the nearest existing road. This step permits estimation of the amount of road constructed under a given management regime, and to determine accessibility in future time steps.

### 3.1.6 Single-Tree Treatments

This sub-model simulates fell and burn and MSMA treatment methods in *suppression* BMUs. First the provincial budget is allocated among *suppression* BMUs proportional to the level of endemic mountain pine beetle state. This model component can also be described from the perspective of a single BMU, since all suppression BMUs are processed independently. Single-tree treatments are generally applied in inaccessible areas or areas with low (endemic and some low mountain pine beetle state) beetle populations. These treatments are applied to individual cells, and the volume is not recovered. The model assumes that the mountain pine beetle state is reduced by one level (i.e. endemic state becomes "no MPB", while low becomes endemic).

## 3.2 Model Outputs

### 3.2.1 Tracking timber volume

Management options involve tradeoffs between various forest values. To understand these tradeoffs, we have found it useful to consider what happens over time to all of the timber volume in the province. In general, timber volume can be:

- Logged or standing (live growing stock or dead)
- Non-pine or pine
- Green (i.e. growing stock not killed by beetles) or standing dead (i.e. killed by beetles and useful for sawlogs, chips, or not useful non-recoverable loss). Note that standing dead volume designations only apply to pine, because beetles do not kill non-pine species.

At any point in time, all timber volume falls into one of the following 10 categories:

- Standing non-pine growing stock
- Logged non-pine

- Standing green pine growing stock
- Standing dead sawlogs
- Standing dead chips
- Standing dead non-recovered loss
- Logged green pine
- Logged sawlogs
- Logged chips
- Logged non-recovered loss (i.e. non-merchantable dead wood in cutblocks)

In most cases, we focus on volume within the timber harvesting landbase. We consider results for the whole province, as well as for each management unit. We look at logged volumes on both an annual and cumulative (over the whole outbreak) basis.

### 3.2.2 Mountain Pine Beetle Outbreak Indicators

Specific mountain pine beetle indicators include:

Area infested (cumulative or annual)
- Volume killed (cumulative or annual)
- Percentage of area infested (cumulative or annual)
- Percentage of volume infested (cumulative or annual)
- Number of hectares in each severity class

### 3.2.3 Inventory Indicators

Limiting Constraints: Track the area of forest made unavailable in each management unit for harvest according to the various constraints. This is output as net and gross values, where the net value is the incremental area constrained after preceding constraints have been accounted for, and the gross value is the total amount that the would be constrained independent of the other constraints. The primary order of constraints applied is:
- minimum harvest age
- road access (if enabled)
- adjacency (if enabled)
- VQO constraints
- Available after all constraints have been applied

This indicator is primarily for model verification.

### 3.2.4 Harvest Indicators

Harvest Report: A range of output values that track key aspects of the harvesting process overall, for each management unit and for each landscape unit:
- annual volume harvested
- annual area harvested
- mean volume per hectare harvested
- percent of harvest target achieved

- mean age harvested
- kilometers of roads built
- area harvested by mountain pine beetle severity state and salvage
- area processed with single tree treatments

BMU report: Values that track key aspects of BMU management:

- BMU type (strategy applied)
- Number of hectares treatable with single tree
- Single tree budget applied in BMU
- Proportion of provincial single tree budget
- Number of hectares actually treated with single tree

### 3.2.5 Spatial output

The following layers are output annually during each simulation:

(i) *Stand age*: age of forest in each cell

(ii) *BMU type*: type of each BMU as assigned during the planning sub-model.

(iii) *Mountain pine beetle severity*: current mountain pine beetle severity class of each cell

(iv) *Mountain pine beetle cumulative kill*: percent of pine volume killed by mountain pine beetle since 1999 in each cell

(v) *Volume per hectare*: cubic metres/ha in each cell (live growing stock)

(vi) *Pine volume per hectare*: cubic metres/ha of pine in each cell (live pine growing stock)

(vii) *Salvageable merchantable volume per hectare*: cubic metres/ha of merchantable (sawlogs or chips) standing dead volume in each cell.

(viii) *Salvageable sawlog volume per hectare*: cubic metres/ha of sawlog volume in each cell .

(ix) *Non-pine harvest volume*: cubic metres/ha of non-pine forest harvested in each cell

(x) *Green pine harvest volume*: cubic metres/ha of green (live) pine harvested in each cell

(xi) *Salvage harvest volume*: cubit metres/ha of salvage harvested in each cell

(xii) *Non-recovered loss volume per hectare*: cubic metres/ha of standing salvageable volume lost to economic decay in each cell

## 3.3 Scenarios Evaluated

A range of scenarios were run to verify the model prior to running the main scenarios described below. These verification scenarios led to model improvements and refinements, as well as greater understanding of the model . We don't describe the results of the verification runs here, and instead focus on scenarios that produced information relevant for project objectives. Some details of the verification of the model can be found in Appendix 3.

At the level of a single grid cell, the behaviour of BCMPB is highly stochastic. However, over the 982 thousand susceptible forest cells in British Columbia this stochasticity averages out, so the main indicators are largely stable between runs at the provincial scale. We ran each scenario for one replicate, but expect to assess how variation in multi-replicate runs affects our results in the upcoming year.

This year we focused on the amount of wood that would be available for harvesting and the non-recovered losses under a "Reference Scenario" that approximated current management. We also ran several sensitivity analyses to examine the impacts of uncertainty in key model parameters. We examined the implications of increasing harvest levels in affected management units defined as all Timber Supply Areas with more than 10% susceptible pine on the timber harvesting landbase. These scenarios are described below.

### 3.3.1 Reference Scenario

The reference scenario is meant to approximate current management and uses our "best guess" relative to the sensitivity analyses scenarios described below.

The reference scenario uses harvest levels based on the Allowable Annual Cut as of September 30, 2004. That is, the harvest level prior to expedited AAC determinations in Lakes, Prince George and Quesnel. We define this as the reference because the increases in harvest resulting from the expedited AAC determinations are intended for the alternative industry and we are not attempting to model the behaviour of that industry. We do examine the implications of the expedited level of harvest as described in Section 3.3.5

The reference scenario models current beetle management strategies. That is, Beetle Management Units are assigned to one of four categories based on the ability to address the outbreak:

- Suppression: address > 80% of the infestation
- Holding Action: address > 50% but <80% of the infestation
- Salvage: address <50% of the infestation
- Monitor: no infestation present.

Harvesting is then focused on leading edge attack where appropriate, and salvage or green tree harvest elsewhere. Single tree treatment levels are set at the 2003 amount.

The reference scenario represents the "mid range" of the sensitivity analyses described in Sections 3.3.2, 3.3.3 and 3.3.4.

### 3.3.2 Sensitivity to assumptions about the end of the infestation

There is considerable uncertainty about when the current outbreak will subside. The reference scenario assumes that the infestation will progress to a logical conclusion based on its observed behaviour over the past six years. The resulting projection is that more than 95% of the susceptible pine will be killed by 2024 and the infestation will simply continue after that, albeit at very low levels.

The reference scenario may over-estimate the amount of pine that will be killed for one of two reasons:

1. It may over estimate the level of kill within each stand. The reference scenario projects that many stand will see 100% of the merchantable pine killed. However, conventional wisdom indicates that during epidemics the mountain pine beetle inundates a stand, preferentially killing the largest diameter trees. Reproduction is proportional to the size of tree beetles breed in, and at a diameter at breast height (dbh) of < 20-25 cm there is a net loss of beetles. Beetles benefit by attacking the large diameter trees and then abandoning a stand, rather than working their way through every tree before moving on. Because of this, attack usually only goes on for 2-4 years in any given stand and some decent sized trees are missed not killed.
2. The infestation may simply collapse well before 2024. Historically, particularly in the Kootenays and the United States, there have been large infestations that have collapsed not because of winter cold weather or host depletion. There are several possible reasons. Weather can still be a factor if it is cool and wet during the flight season, which tends to stagger the flight and disrupt the synchrony of the population (for mass attack etc). Another possibility is that beetle are less successful in mixed stands and mountainous areas where pine is more difficult to find. A third possibility is that as an epidemic grows an increasing proportion of beetles are left in already decimated stands, which results in a net loss of beetles.

Given these possibilities we modeled 4 separate scenarios. In two of them we reduced the maximum level of kill to an average of 66% or 80% of the merchantable pine to simulate the first rationale described above. In these scenarios the infestation continues (past 2024) but the level of kill in each stand is less. In the other 2 scenarios we modeled the infestation as in the reference scenario but simply stopped it in 2011 and 2014 when approximately 66% and 80%, respectively, of the merchantable pine is projected to be killed.

### 3.3.3 Sensitivity to assumptions about shelf-life

Specification of the shelf-life of beetle killed pine for any given purpose or product is difficult because shelf-life is a complex concept composed of three inter-related variables:

1. the rate at which the wood will deteriorate given its characteristics and the characteristics of its location in the environment, particularly climate and soil moisture;
2. the capability of industry to utilize wood of various qualities given the state of engineering and the availability of machinery and processes; and
3. the demand for, and price of, the various products that can be made from beetle killed wood.

We have very little actual information about the first aspect of shelf-life. While there is a growing body of work on the engineering aspects of utilizing beetle killed wood it is difficult or impossible to accurately project the demand for, and price of, those products. Therefore, we are unlikely to "know" the shelf-life. At best we can model shelf-life within reasonable bounds and examine the implications of that uncertainty.

# BCMPB v2: Results of year 2 of the project

We consider the estimates of biological rate of deterioration provided by Thrower (2003) to be "conservative" and we use them to represent the reference scenario. We model pessimistic and optimistic versions by subtracting and adding a constant amount of time, respectively, with one exception. The optimistic shelf-life in dry subzones is more different (optimistic) than the differences for the moist and wet subzones.

We model a reference[1], optimistic and pessimistic set of shelf-life assumptions as follows:

**Reference**

All volume available for all products for **3 years** after death.

| Subzones | Time to complete deterioration of sawlog volume | Time to complete deterioration of "alternative" volume |
|---|---|---|
| Dry | 7 | 15 |
| Moist | 6 | 13 |
| Wet | 5 | 10 |

Note that this means that after 4 years in a moist subzone two thirds of the volume would be available for sawlogs.

**Pessimistic**

All volume available for all products for **2 years** after death.

| Subzones | Time to complete deterioration of sawlog volume | Time to complete deterioration of "alternative" volume |
|---|---|---|
| Dry | 5 | 10 |
| Moist | 4 | 8 |
| Wet | 3 | 5 |

Note that this means that after 3 years in a moist subzone one half of the volume would be available for sawlogs.

**Optimistic**

All volume available for all products for **4 years** after death.

| Subzones | Time to complete deterioration of sawlog volume | Time to complete deterioration of "alternative" volume |
|---|---|---|
| Dry | 15 | 25 |
| Moist | 8 | 18 |
| Wet | 7 | 15 |

Note that this means that after 6 years in a moist subzone one half of the volume would be available for sawlogs.

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[1] based on information used in Thrower 2003

These relationships are shown graphically in Figure 1 where "alternative volumes" are labeled "chips".

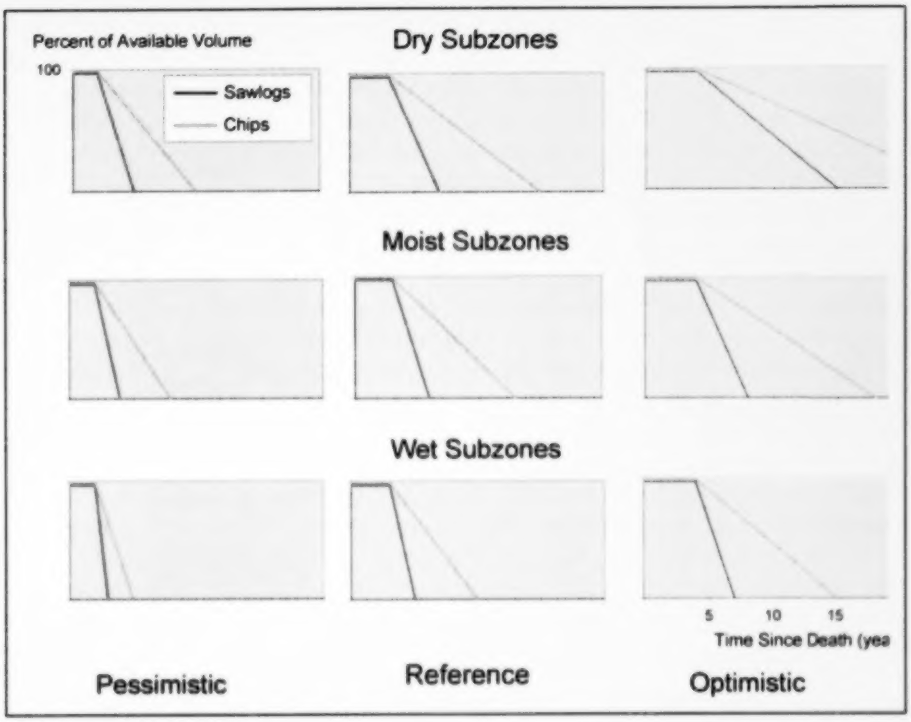

Figure 2. ***Relationship between time since death and the amount of volume available for the sawlog and "alternative" (chip) industries in dry, moist and wet subzones under pessimistic, reference and optimistic assumptions.***

### 3.3.4 Sensitivity to assumptions about salvage priority

It is not completely clear how the forest industry will respond to the opportunity to salvage the beetle killed wood. Timber supply analyses model the salvage of dead wood using a harvest queue that sorts the stands starting with the highest percentage of pine (pure pine) and the highest percentage kill (100% kill). Stands are then "ordered" in decreasing percentage pine and percentage kill. It is assumed that the stand will be harvested in this order. However, achieving this harvest order given operational reality is not possible. Therefore, a minimum percentage pine and percentage kill that can be considered salvage is specified and the industry must operate "above" that minimum. It is conceivable that some licensees will, in fact, salvage the dead wood in the opposite order to that modeled in the timber supply review. That is, they will start with the stands with the minimum acceptable percentages of pine and dead wood.

We model three possible salvage priorities. In each case a stand can only be considered salvage if it has more than 50% pine and more than 50% of the pine has been killed. Stands must also have a minimum of 100 $m^3$ of live and dead wood suitable for dimensioned lumber production. The salvage priorities are:

1. Maximum dead volume. This is the priority used in the reference scenario and represents our attempt to model the assumptions used in timber supply analyses. The harvest model orders the acceptable salvage stands based on dead volume and starts with the highest dead volume stand, given other constraints such as the timber harvesting landbase and distance to roads.
2. Maximum live volume: This priority represents the "opposite" of the reference scenario. The model orders the acceptable salvage stands based on live volume in the stand and starts with the highest live volume stand.
3. Maximum total volume: This priority represents a "compromise" between the first two scenarios. The model orders the acceptable salvage stands based on the total volume, both live and dead, in the stand and starts with the highest total volume stand.

### 3.3.5 Implications of increasing harvest levels

One of the principal forest management tools available to the Ministry of Forests for dealing with the implications of the outbreak is the Allowable Annual Cut. In several management units harvest levels have been increased in an attempt to slow the progression of the outbreak. The harvest levels have also been increased in the Lakes, Prince George and Quesnel Timber Supply Areas to facilitate salvaging of the beetle killed wood. We model increases in harvest levels to examine the implications of doing so. The following harvest levels were examined:

- **Reference Scenario Harvest**. Based on AAC levels as of September 30, 2004. That is, levels prior to the expedited increases in the Lakes, Prince George and Quesnel Timber Supply Areas
- **Expedited Harvest**: Based on AAC levels as of October 1, 2004. That is, levels including the expedited increases in the Lakes, Prince George and Quesnel Timber Supply Areas.
- **Up Now Harvest**: Expedited harvest levels plus increases in harvest levels in all other management units immediately. Increases in harvest level were based on the percentage of pine on the timber harvesting land base in the management unit plus a constant increase for all units:
    - New Harvest Level = Old Harvest Level + ( Old Harvest Level * (percent pine + 20%)

      This equation approximates uplifts considered for some management units, and results in a minimum increase of 32% in Robson Valley and a maximum increase of 74% in Williams Lake
- **Up Peak Harvest**: The increases in harvest were determined as in the previous case but, rather than increasing immediately, the increases were postponed until one year after the peak in annual kill in the management unit. This simulates postponing the increase until after there is no longer any attempt in the management unit to control the outbreak.

# BCMPB v2: Results of year 2 of the project

- **Up Peak Double Harvest**: The increases were timed as in the previous case but the amount that they were increased was doubled. That is minimum increase of 64% in Robson Valley and a maximum increase of 158% in Williams Lake

# 4.0 Results and Discussion

## 4.1 Forests at Risk to Mountain Pine Beetle

We estimate that in 1999, the "beginning" of the current outbreak, there were a total of 9.8 billion $m^3$ of timber with a diameter at breast height greater than 12.5 cm (the "primary utilization level") in the province of British Columbia (Table 1)[2]. Of this, slightly less than one quarter was one of the 5 pine species found in the province (Limber, Lodgepole, Western White, Whitebark and Ponderosa Pine; *Pinus flexilis, contorta, monticola, albicaulis*, or *ponderosa*, respectively). However, pine makes up 30% of the volume on the timber harvesting landbase, a much higher proportion than on the non-contributing landbase (18%) (Table 1).

Of the total pine volume in the province, approximately 1.8 billion $m^3$ is susceptible to mountain pine beetle attack (Table 2) by our definition (older than 60 years and in a climatically suitable Biogeoclimatic zone – i.e. not AT, BWBS, CDF, CWH, SWB). Although mountain pine beetle has caused significant damage to coastal pine in the past (Collis and Alexander 1966) we find it convenient to exclude these areas for the purpose of this analysis, primarily because the current outbreak has not yet developed a significant coastal component. Of the 1.8 billion $m^3$ of susceptible pine, 1.2 billion $m^3$ is in the timber harvesting landbase. This represents the timber volume "at risk" of loss.

Table 1. ***Billions of cubic metres of timber volume in British Columbia prior to the outbreak.***

| | timber harvesting landbase | | |
|---|---|---|---|
| | No | Yes | Total |
| Pine | 1.0 | 1.3 | 2.3 |
| Other Species | 4.3 | 3.3 | 7.5 |
| Total | 5.2 | 4.6 | 9.8 |

Table 2. ***Billions of cubic metres of pine volume in British Columbia prior to the outbreak.***

| | timber harvesting landbase | | |
|---|---|---|---|
| Susceptible to mountain pine beetle | No | Yes | Total |
| No | 0.3 | 0.2 | 0.5 |
| Yes | 0.6 | 1.2 | 1.8 |
| Total | 1.0 | 1.3 | 2.3 |

The forested area of British Columbia is approximately 62 million hectares. Of that area 32 million hectares are in the Biogeoclimatic Zones that are climatically suitable for mountain pine beetles (see above). Forty six percent of the total forested area in the province contains some pine. In the susceptible BEC Zones 57% of the forest stands contain some pine component (Table 3).

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[2] Our volume and areas estimates are based on a combination of data sources, described in Appendix 1.

Table 3. *Forested area with and without pine in the susceptible Biogeoclimatic Zones (millions of hectares).*

| | timber harvesting landbase | | |
|---|---|---|---|
| Tree Species | No | Yes | Total |
| No Pine | 8 | 6 | 14 |
| With Pine | 7 | 11 | 18 |
| Total | 15 | 17 | 32 |

The proportion of pine in forested stands varies significantly throughout the province (Table 4). Throughout the susceptible BEC Zones 36% of the pine is in forests with high percentages of pine (>=90%) but over 30% is in areas with less than 40% pine. These percentages are highly variable throughout the province (Table 4).

Table 4. *Percentage of pine in stands in the susceptible BEC Zones and selected TSAs.*

| Percent Pine | Entire Susceptible Area | Arrow TSA | Quesnel TSA |
|---|---|---|---|
| Low (<40%) | 33% | 69% | 14% |
| Moderate (40 - 89%) | 32% | 25% | 27% |
| High (90 - 100%) | 36% | 6% | 58% |
| Total | 100% | 100% | 100% |

## 4.2 Volume and area affected by mountain pine beetle in 2004

Based on the provincial aerial overview surveys we estimate that a total of 280 million $m^3$ of pine have been killed by mountain pine beetle as of 2004. This estimate is for the "observable" (red) dead pine and does not include estimates of "green attack". Of that, 170 million $m^3$ were in the timber harvesting landbase (14% of the total susceptible volume). The area affected by mountain pine beetle is difficult to summarize because of variability in proportion of the pine that is affected in any given place. We estimate that more than 1 million hectares of forest were in an "incipient" stage of infestation (> 0 and <1% of the pine killed) in 2004. Approximately 7 million hectares had experienced more than 1% of the pine killed by 2004. This represents 40% of the area of susceptible pine. This estimate is much higher than the 5 million hectares estimated by the provincial aerial overview data in 2003 (Westfall 2004) because that estimate only includes the current annual attack. We consider the cumulative attack over all years. We also estimate more attacked area because the method we use to convert the polygon based aerial overview data to a grid based map tends to increase the apparent area of the attack (though it has no effect on the volume of the attack). According to our grid-based data, the total area with any mountain pine beetle infestation (including trace amounts [<1%]) in 2004 is more than 8 million hectares whereas the total area estimated by the 2004 aerial overview survey is 7 million hectares (Westfall 2004). The majority of susceptible pine forest had experienced some level of mortality by 2004 (Table 5). However, the amount of pine killed is highly variable throughout the province (Table 5, Figure 3). The major concentration of kill by mountain pine beetle in 2004 was centered on the Quesnel, southeastern Nadina and Vanderhoof Forest Districts.

Table 5. *Proportion of area with pine by class of cumulative kill for all susceptible pine and selected management units.*

| Cumulative Kill at 2004 | All Susceptible Pine | Arrow TSA | Quesnel TSA |
|---|---:|---:|---:|
| No kill | 43% | 48% | 0.5% |
| >0 and <1% | 9% | 13% | 0.2% |
| 1 - 10 % | 17% | 18% | 5% |
| 11 - 30 % | 13% | 14% | 30% |
| 31 – 50% | 8% | 4% | 30% |
| 51 - 70 % | 5% | 1% | 20% |
| 71 - 100 % | 5% | 1% | 15% |
| Total | 100% | 100% | 100% |

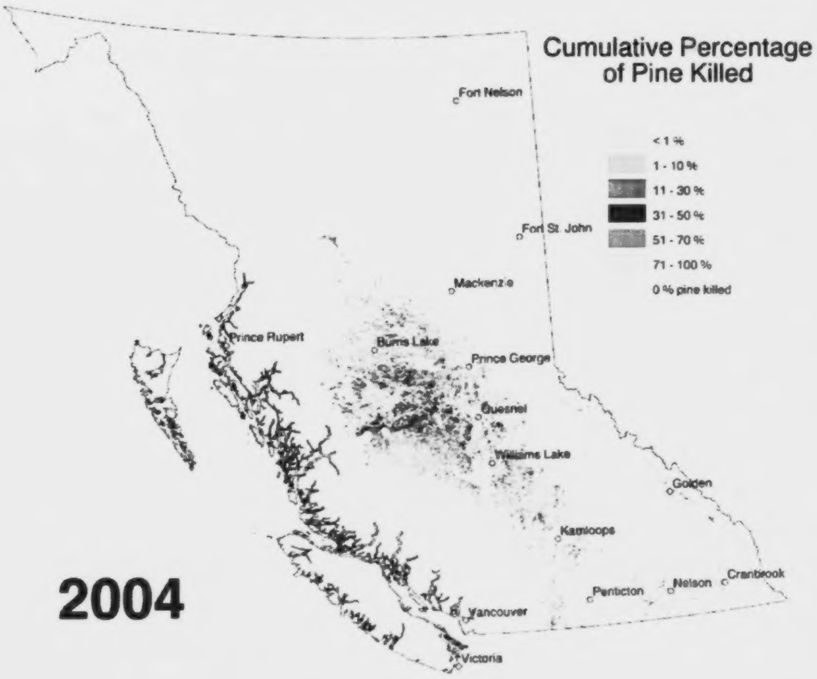
Cumulative Percentage of Pine Killed
< 1 %
1 - 10 %
11 - 30 %
31 - 50 %
51 - 70 %
71 - 100 %
0 % pine killed
Fort Nelson
Fort St. John
Mackenzie
Prince Rupert
Burns Lake
Prince George
Quesnel
Williams Lake
Golden
Kamloops
Penticton
Nelson
Cranbrook
Vancouver
Victoria
2004

Figure 3. *Observed cumulative percentage of pine killed in 2004.*

(A high resolution (3 meg.) version of this figure is available http://www.for.gov.bc.ca/hre/BCMPB/BCMPB_pctkill2004_Input.pdf)

### 4.3 Projection of the Reference Scenario.

We project that the annual volume of pine killed will peak during the 2006 flight at more than 90 million $m^3$ of merchantable pine in the timber harvesting landbase. The trees killed that summer will not be "observed" by the provincial aerial overview until the summer of 2007 (Figure 4). It is important to note that we also project that during 2006 we will harvest over 14 million $m^3$ of live pine as a "by-catch" of our efforts to control the outbreak and salvage dead timber. By the end of 2006 approximately 40% of the susceptible pine will have been killed or harvested. Over the next 6 or 7 years another 40% may be killed or harvested. We expect that significant volumes of pine will continue to be killed at least until 2015 and we project that the volume killed will not decrease to pre-outbreak levels until after 2020. In general the outbreak initially expands rapidly for several years because it currently is centered on very high quality beetle habitat (large areas of continuous mature pine). The outbreak subsides as that habitat is depleted and the beetles move into less desirable habitat (smaller areas of more dispersed pine).

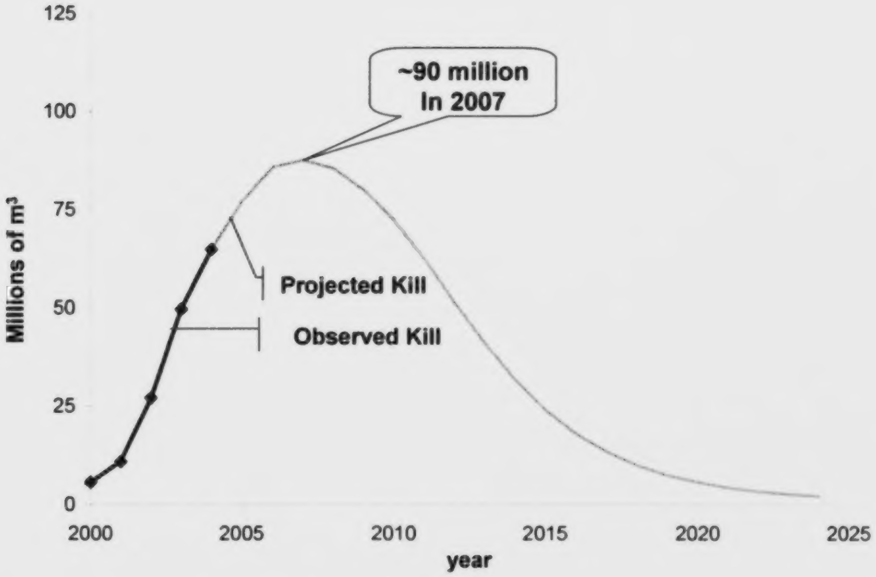

Figure 4. *Observed and Projected (for the Reference Scenario) Annual Volume of Pine Killed in the Timber Harvesting Landbase.*

We project substantial variability in the timing of the peak in annual kill in different areas of the province (Figure 5). Figure 5 shows the projected proportion of the pine that will be killed annually for each Timber Supply Area where more than 10% of the merchantable volume is susceptible pine. Note that the Prince George TSA is divided into its individual districts (Fort St. James, Prince George and Vanderhoof) because of the very large size of this TSA and the variability in amounts of kill throughout the area. The management units are listed on the right in descending order of the proportion of pine killed in 2004. Those units with the higher proportions of pine killed have an earlier peak in annual kill. Quesnel is already past the peak in annual kill (25% in 2003) but still has the highest proportion of pine killed in 2004 (15%). Vanderhoof is the only other unit that has passed the peak in annual kill. The Lakes TSA will experience 2 peaks in annual kill. One has already occurred in 2003 when a large proportion of the pine south of Ootsa Lake was killed. We project a second peak in annual kill in the Lakes TSA in 2006 when the areas of high volume pine in the west central portion of the TSA will be heavily infested.

Units with lower proportions of pine killed are generally further from the center of the outbreak and thus take longer to experience the peak in annual kill. In general, the later the occurrences of the peak in annual kill, the lower the percentage of pine that is killed at the peak. We attribute this to the fact that those units that peak late tend to have relatively poor, discontinuous beetle habitat.

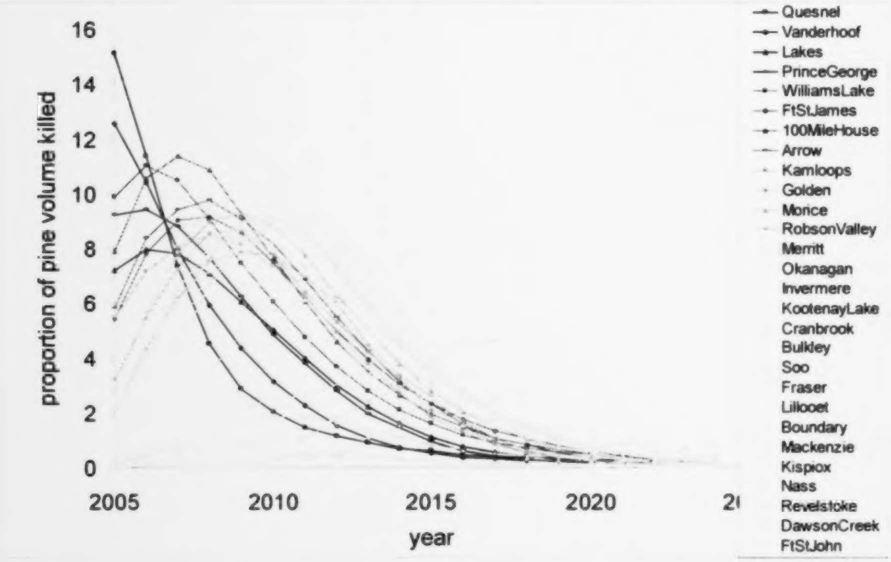

Figure 5. *Effect of initial proportion of volume killed on the progression of the outbreak.*

The Reference Scenario projects that over 95% of the susceptible pine on the timber harvesting landbase will be killed by 2024 (Figure 6). It should be noted that this is a "worst case" scenario. The projection indicates how long it would take to get as bad as it could possibly get. Past outbreaks of mountain pine beetle have been "stopped" by very cold winters (Wood and Unger 1996). It is not inconceivable that cold winters may slow or stop the progression of this outbreak. However, it is very unlikely that the entire outbreak area will experience sufficiently cold weather to affect a significant proportion of the beetle population. Our projection may also represent an over estimate because we project that virtually all the volume within all stands will eventually be killed by mountain pine beetle. We conducted sensitivity analyses to assess the implications of these 2 assumptions (described in Section 3.3.2 and reported in Section 4.5).

We are not aware of any systematic survey of kill rates that could definitively tell us what proportion of trees might be killed by beetles in a typical outbreak, but the suggestion from beetle researchers is that beetles rarely kill more than 90% of the volume in a stand. From their collective experience, researchers from the Canadian Forest Service suggest that, in pure pine stands subject to heavy beetle pressure, 70% of the stems and 90% of the standing volume might be killed by beetles. Over the whole landscape, they suggest the average is probably closer to 50-60% of the stems and 60-70% of the volume. An incomplete survey of the literature corroborates these opinions: 32-92% of merchantable basal area killed in 10 study areas in Wyoming and Idaho (Amman and Baker 1972); 50 – 75% of stems killed in 40 stands in Northern Utah (Stone and Wolfe 1996); and 41- 67% of stems killed in 10 stands in southwestern Yellowstone (Romme et al 1986). Nonetheless, a brief survey of heavily infested stands near the center of the outbreak indicates that kill levels of 100% of the merchantable volume (>12.5 cm dbh) are not uncommon (Appendix 5). Personal communications with MOF district staff in Nadina, Quesnel and Vanderhoof districts corroborate these observations.

Despite the fact that all of the merchantable volume may be killed there are good biological reasons to expect that beetles will not kill all the trees. Even within uniform-aged pure pine stands there is variation in tree diameter and vigour. Smaller trees tend to have thinner phloem, which provides beetles with less food, and also protects them less well from drying (Safranyik et al 1999). Beetles tend to attack large trees first (Geiszler et al. 1980; Mitchell and Preisler 1991), where they can reproduce successfully. Once they have exhausted the quality food supply, they turn to smaller trees, but will survive less well in these trees, causing populations to decline before all the small trees can be killed. Beetles might also tend to do more poorly in stands with fewer live pine trees. It has been established that thinning lodgepole pine stands reduces forest susceptibility to beetles (Amman et al. 1988; Mitchell et al. 1983; Preisler and Mitchell 1993; Waring and Pitman 1985). This might be because the vigour of trees increases in less crowded stands, because it is more difficult for beetles to switch between trees that are further away from one another, or because the microclimate in more open stands is less favourable for beetles. Whatever the explanation, it is reasonable to expect that stands thinned by previous beetle mortality are also less favourable for beetles.

By 2009, our model projects that 14 million ha of susceptible pine (92%) will have some level of infestation by mountain pine beetles and over 615 million $m^3$ of pine (~60%) on the timber harvesting landbase will have been killed (Figure 6).

That area will be distributed throughout the susceptible range with concentrations of current attack in the northern and southern portions (Figure 7).

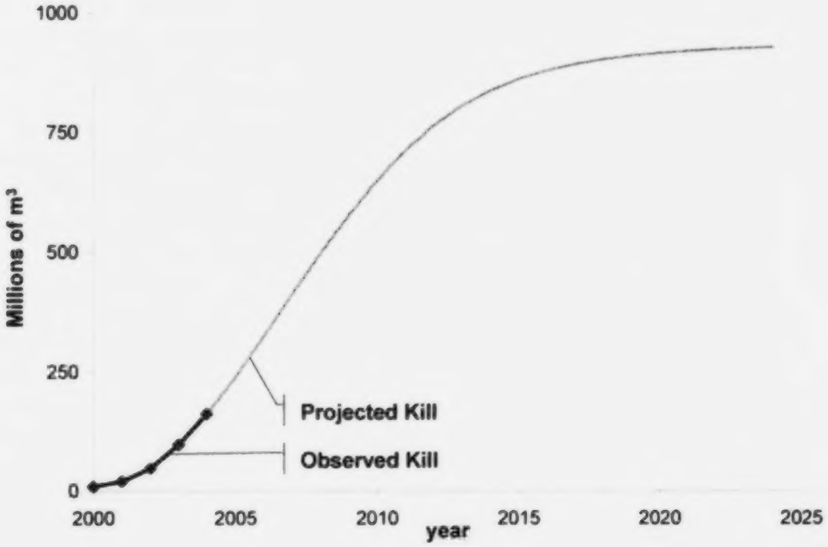

Figure 6. *Observed and projected (for the Reference Scenario) cumulative volume of pine killed in the timber harvesting landbase.*

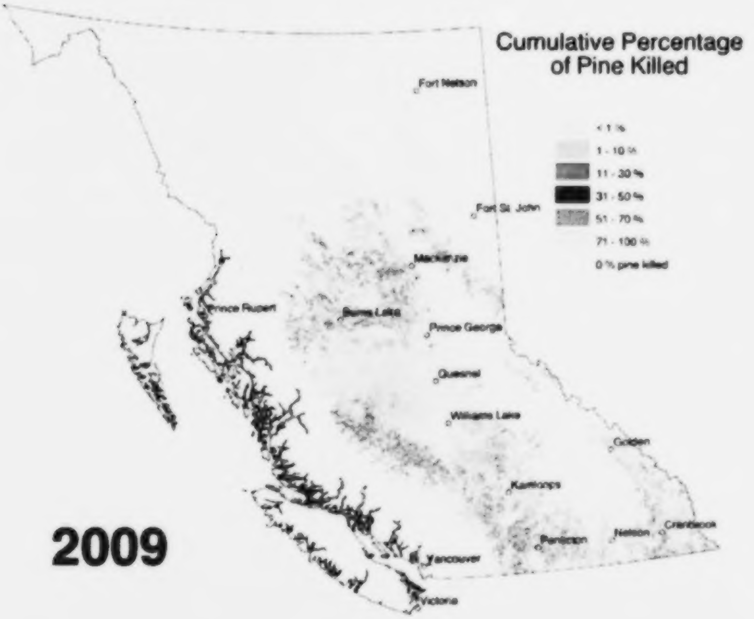
Cumulative Percentage of Pine Killed
< 1 %
1 - 10 %
11 - 30 %
31 - 50 %
51 - 70 %
71 - 100 %
0 % pine killed
Fort Nelson
Fort St. John
Mackenzie
Prince Rupert
Burns Lake
Prince George
Quesnel
Williams Lake
Golden
Kamloops
Cranbrook
Nelson
Penticton
Vancouver
Victoria
2009

Figure 7. *Projected cumulative percentage of pine killed in 2009 under the Reference Scenario.*

(A high resolution (3 meg.) version of Figure 7 is available http://www.for.gov.bc.ca/hre/BCMPB/BCMPB_pctkill2009_Output.pdf)

## 4.4 Volume of Pine Harvested, Available and Lost under the Reference Scenario.

Figure 8 illustrates the effect of the mountain pine beetle outbreak and associated management activities on pine volume within the timber harvesting landbase for the 21 Timber Supply Areas where more than 10% of the volume on the timber harvesting landbase is susceptible pine (100 Mile House, Arrow, Boundary, Bulkley, Cranberry, Cranbrook, DawsonCreek, Golden, Invermere, Kamloops, Kootenay Lake, Lakes, Lillooet, Mackenzie, Merritt, Morice, Okanagan, Prince George, Quesnel, RobsonValley, Williams Lake).

As described in Section 3.1.2, we report on four categories of pine:

- Live pine: merchantable and susceptible pine that has not been killed by mountain pine beetles
- Sawlogs: dead pine that has been killed recently enough that it is suitable for the manufacture of dimensioned lumber products.

- Chips: pine that has been dead long enough that it is no longer suitable for dimensioned lumber products but is still useable for "alternative" products such as pulp, oriented strand board or bio-fuel.
- NRL: Non-recovered loss. Pine that has been dead for so long that it is no longer useable even for alternative products.

In Figure 8 we present the volumes that are projected to be in each of these four categories through time, further subdivided into volumes that have been harvested and volumes that are still standing. Note that the "Logged NRL" category represents the volume of "residue" that will occur in harvested blocks. This is volume that will not be useable but must be logged because it will be intermixed with sawlog and chip volume. Note also that the Logged Chips are, effectively, a by-product of harvesting. As stated previously, we are modeling the traditional dimensioned lumber industry. The model is "looking for" sawlogs. The chips that it harvests are, again, intermixed with the sawlogs and live pine that are harvested. We do assume that the harvested chips will contribute to the target harvest level.

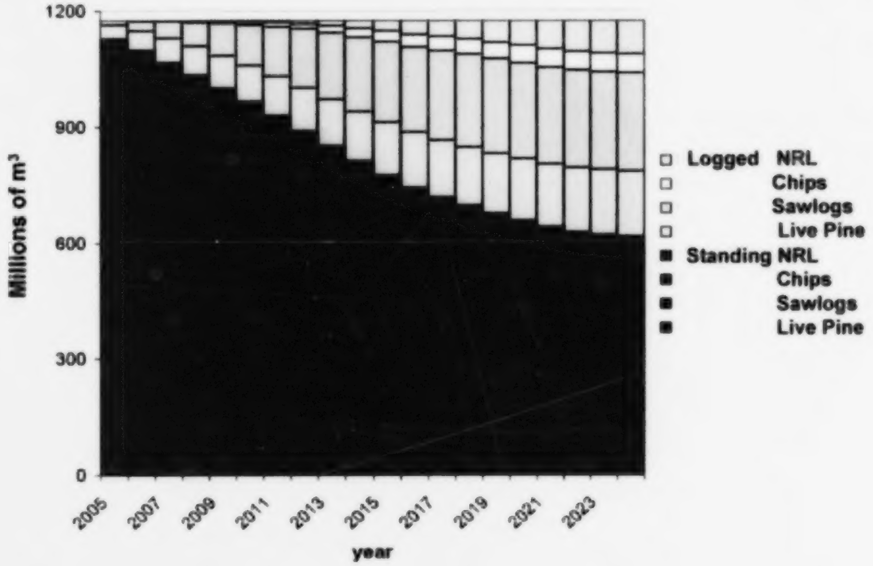

Figure 8. *Projected proportion of susceptible and merchantable pine volume on the timber harvesting landbase in various categories under the Reference Scenario.*

In 2005 we project that there will be 900 million $m^3$ of live pine and 230 million $m^3$ of standing dead pine of which 220 million $m^3$ will still be useable as sawlogs. By the end of the projection we estimate that there will be 80 million $m^3$ of live pine in the 21 TSAs and the combined standing and logged non-recovered losses will amount to 580 million $m^3$. The volume of available dead sawlogs will peak in 2009 at 350 million $m^3$ and will not fall below 100 million $m^3$ until 2017. The volume of available chip quality pine will not peak until 2104 at 190 million $m^3$ and will not drop below 100 million $m^3$ until 2020.

Over the next 20 years we estimate that the harvest in the 21 TSAs will consist of (in millions of $m^3$):

| | |
|---|---|
| Non pine: | 490 |
| Live pine: | 170 |
| Sawlog quality dead pine: | 250 |
| Chip quality dead pine | 50 |
| Dead pine residue (NRL) | 90 |

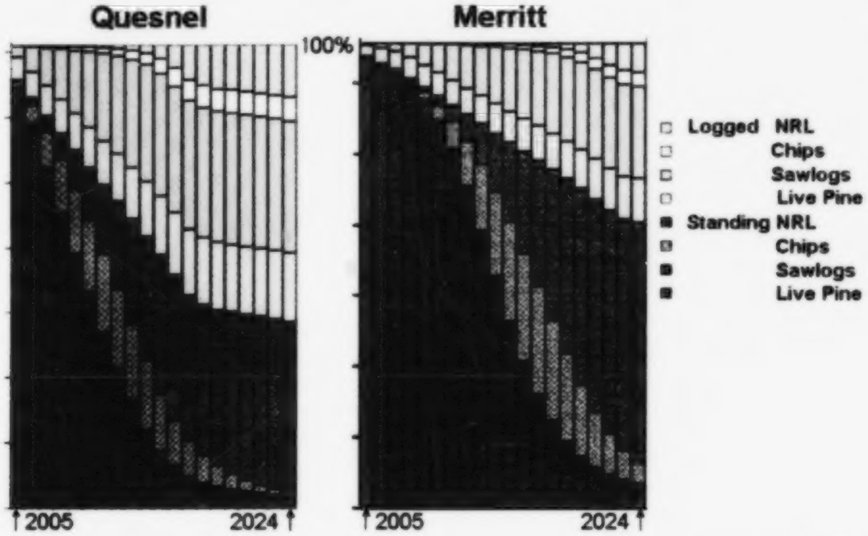

Figure 9 *Projected proportion of susceptible and merchantable pine volume on the timber harvesting landbase in various categories under the Reference Scenario in the Quesnel and Merritt TSAs.*

The general trend remains consistent throughout the province but the specifics vary substantially depending on the management unit examined (Figure 9). In Quesnel, because of the already advanced state of the outbreak, the peak in standing dead sawlogs occurs in 2006. This does not occur in Merritt, where the infestation is beginning, until 2011. In Quesnel we project that 70% of the pine volume would be lost under the pre-expedited harvest level and 60% will be lost under the expedited increase. In Merritt, under current harvest levels 60% of the pine volume will be non-recovered losses by 2024.

## 4.5 Sensitivity to assumptions about the end of the infestation

We made four sets of assumptions about the end of the infestation in addition to the reference scenario assumption (described in Section 3.3.2). These assumptions result in infestation trajectories shown in Figure 10.

# BCMPB v2: Results of year 2 of the project

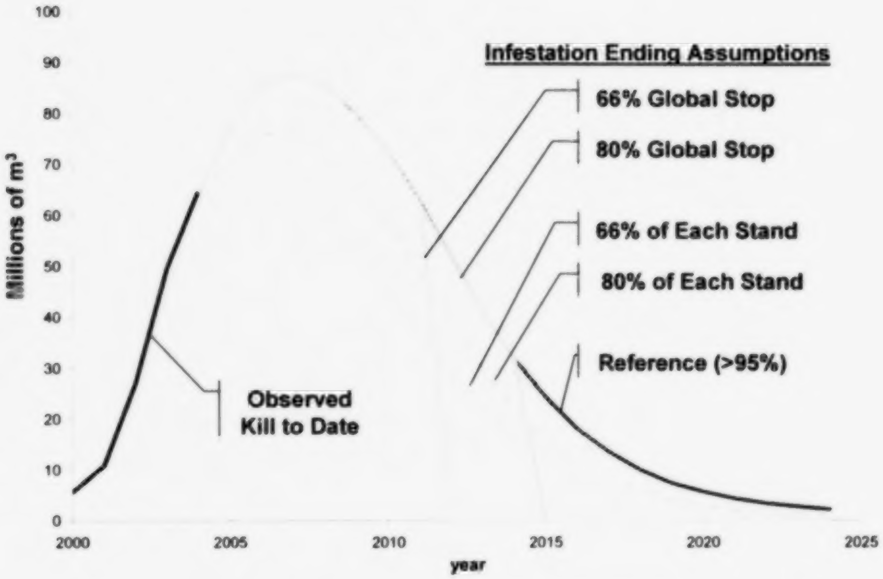

Figure 10. *Annual volume killed on the timber harvesting landbase under different assumptions about the end of the infestation.*

The results are simply an explicit consequence of the assumptions that were made. As discussed in some detail in Section 4.3 we have no way of actually knowing when the infestation will end or which of the five assumptions is most reasonable. We note that if we assume that, on average, only 66% of the pine volume in each stand will be killed, the result is that the infestation has to "slow down" in 2005 before increasing in intensity again. This is an unreasonable behaviour and, therefore, the only other possibility that would make this assumption reasonable is that we have significantly over-estimated the observed kill to date, particularly in heavily infested areas. We have no indication that is so, and believe we can reject this assumption about the end of the infestation at a provincial scale. However, it is still possible that beetles will kill less at the periphery of the infestation. The "global stop" assumptions are modeled in a way that is too extreme. That is, we would not expect the infestation to completely end in one year. However, given the uncertainty about these assumptions modeling a more realistic global stop seems unwarranted, particularly given that it would have little or no impact on management conclusions.

The five different infestation assumptions have a dramatic impact on the levels of non-recovered losses anticipated to occur by 2024 (Figure 11). Total non-recovered losses differ by 200 million $m^3$ between the most optimistic and most pessimistic assumptions. However, if we reject the "66% of each stand" assumption as being unreasonable because of the behaviour it requires for the outbreak then the difference between the most optimistic and most pessimistic assumptions is only 100 million m$^3$. These conclusions are based on an examination of the state of the system at 2024. There is very little difference between the Reference scenario (>95% kill) and the "80% Global Stop" assumption at this time. However, non-recovered losses for both assumptions will continue to increase after 2024 and the difference between these two assumptions will also increase. There is very little difference in non-recovered losses among the different assumption for at least ten years because under all assumptions substantial volumes continue to be killed for at least 7 more years and the reference scenario assumptions about shelf-life result in no losses of useable volume for 3 years after death.

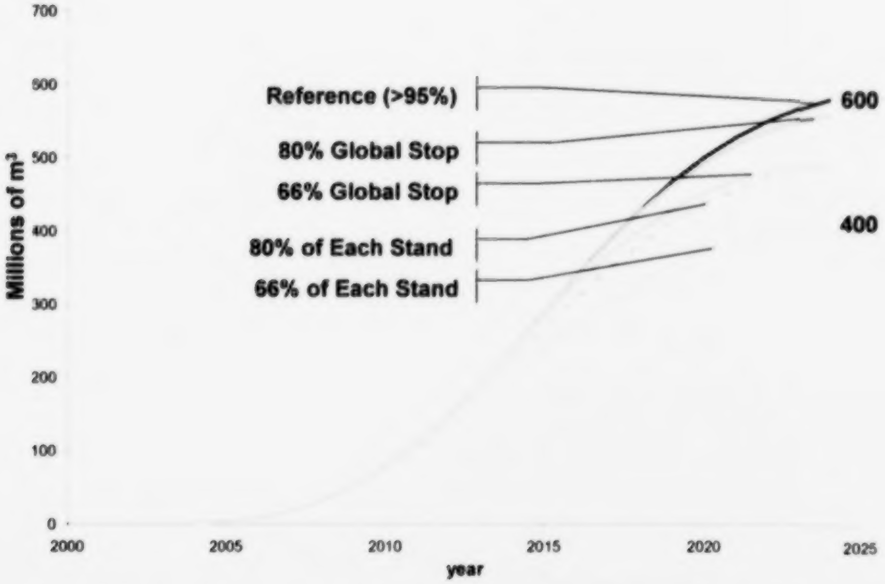

Figure 11. *Cumulative non-recovered losses under five different assumptions about the end of the infestation.*

# BCMPB v2: Results of year 2 of the project

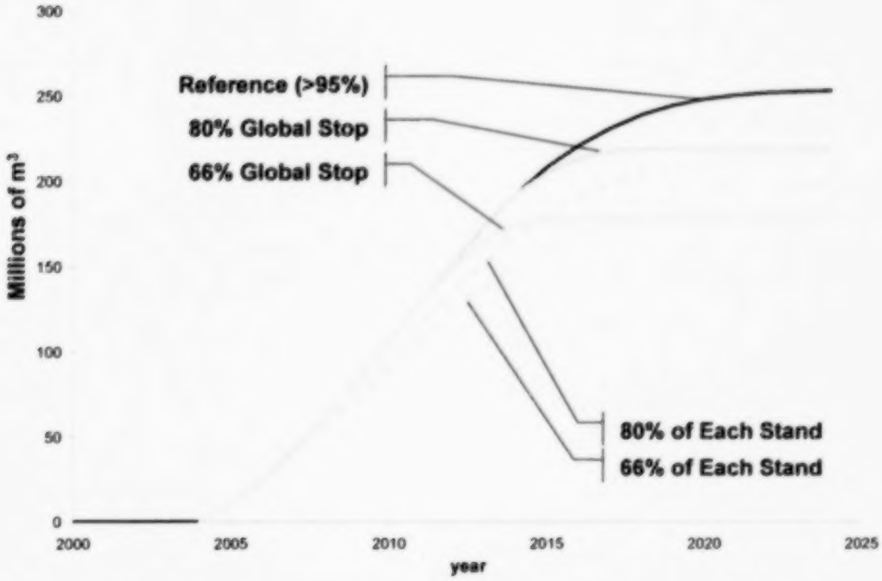

Figure 12. *Cumulative volume of dead sawlog quality pine harvested under different assumptions about the end of the infestation.*

If one assumes that the infestation will completely stop at some point (globally after 66% or 80% of the pine is killed) then the harvest of dead sawlog quality pine stops shortly after the infestation ends (Figure 12);no new dead sawlogs are being created and the existing ones have a relatively short shelf-life. However, if one assumes that the infestation continues but kills only a portion of each stand (66%, 80% or more than 95%) then the volume of dead sawlog quality pine that is harvested continues to increase, albeit slowly, near the end of the projection because new sawlog quality dead pine continues to be created.

A somewhat unexpected corollary is demonstrated by Figure 13. If the infestation stops abruptly, the amount of logged non-recovered loss (residue) is much lower than if the infestation continues to kill some amount of pine in each stand. The reason is that if the infestation stops abruptly then harvesting focuses entirely on salvage for some period, resulting in an increase in harvested NRL over the reference scenario. Harvesting then switches fairly rapidly from salvage to the harvest of live pine and non-pine stands as the dead pine deteriorates beyond usability as sawlogs. Once harvesting is concentrated on live pine and non-pine, the amount of logged non-recovered loss begins to level off although it does not end completely because there is still some dead pine mixed in with the live wood that must be dealt with. In contrast, if the infestation continues to kill pine at some level then opportunities for salvage continue to be generated. This results in a concomitant requirement to log non-recovered loss at relatively high levels because it is mixed in with the salvageable pine. Unexpectedly, the amount of logged non-recovered loss is higher if we assume that the infestation will kill on average 80% of pine in each stand rather than more than 95% of the pine. The reason is that if the infestation kills a lower proportion of the pine in a mixed stand then that stand is more likely to remain a viable harvesting opportunity once the model switches from salvaging to harvesting live volume. However, because there is a substantial harvest of mixed pine stands that have been affected there is a concomitant requirement to deal with the dead wood in those stands. If all, or almost all, of the pine in mixed stands is killed then those stands are more likely to be undesirable when the model switches to harvesting live wood. As a result, the non-recovered loss is simply left in the woods, at least in the short term (before 2024). On the other hand, if a maximum of 66% of each stand is killed, then even more mixed stands remain viable when the model switches from salvaging to harvesting live volume. However, such stands on average have lower levels of mortality and so not only is the proportion of non-recovered loss in each stand lower, but fewer stands need to be harvested to meet the harvest target.

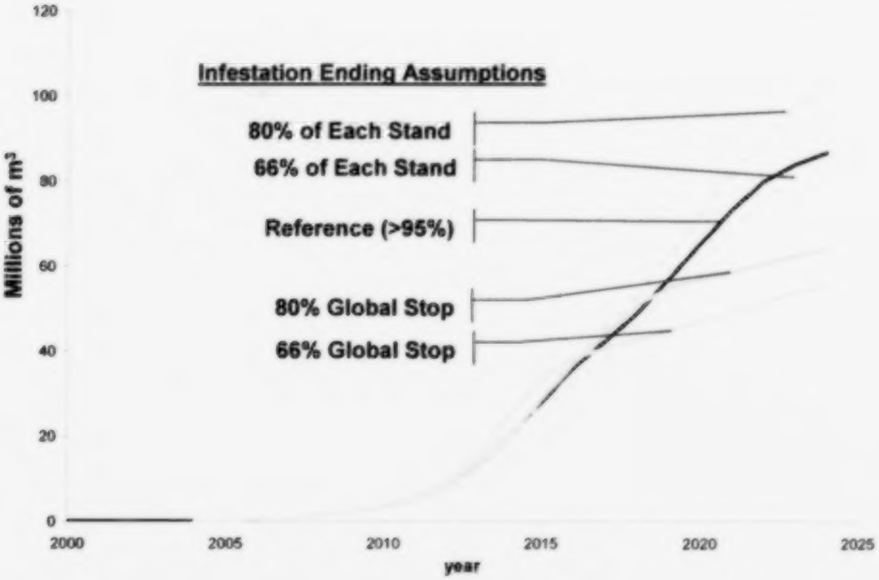

Figure 13. *Cumulative volume of logged non-recovered loss (residue) under different assumptions about the end of the infestation.*

### 4.6 Sensitivity to assumptions about shelf-life

There is virtually no published information available about the shelf-life of beetle killed pine in British Columbia. The Mountain Pine Beetle Initiative (MPBI) of the Canadian Forest Service is funding a substantial amount of work on the development and delivery of market support information on the physical and chemical properties of post-beetle wood (strategic initiatives B2 and B3 http://mpb.cfs.nrcan.gc.ca/research/active_e.html). That information is not relevant to the topic of how long a beetle killed tree remains useable for a given purpose. The MPBI is also funding work on that topic but, unfortunately, none of that information is yet available. We expect that the forest industry has collected some information on shelf-life but that information, if it exists, is proprietary and we are not privy to the results.

As described in Section 3.3.3 we used the Thrower (2003) information to develop a "conservative" estimate of shelf-life for the reference scenario that is most applicable to the plateau ecosystems in central British Columbia where there is the highest volume of pine and where the outbreak is most intense. Given the significant uncertainty about shelf-life we also developed "pessimistic" and "optimistic" versions of the parameters derived from Thrower (2003).

The effect of shelf-life on cumulative non-recovered losses is shown in Figure 14. This sensitivity differs from the sensitivity to assumptions about the end of the infestation (Section 4.5) in that the different scenarios about shelf-life begin to diverge immediately. In 2005 there are already approximately 280 million m$^3$ of standing dead pine that is suitable for sawlogs. Much of that wood has been standing dead for long enough that it will begin to rapidly deteriorate in quality given pessimistic shelf life assumptions.

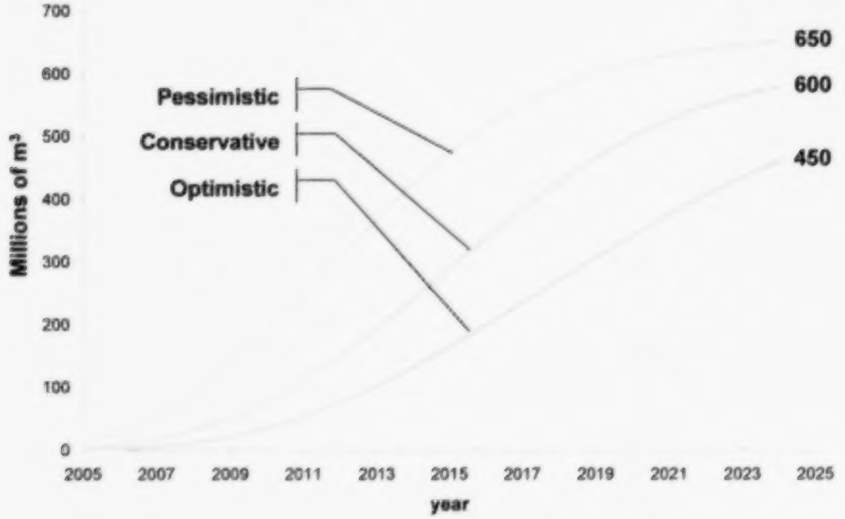

Figure 14. *Cumulative non-recovered losses under three sets of assumptions about the shelf-life of beetle killed pine.*

The differences between the pessimistic and optimistic assumptions about shelf-life are not symmetrical around the reference scenario (conservative assumptions). This is due solely to the optimistic assumptions about shelf-life in dry ecosystems.

In those ecosystems we optimistically assume that the some wood will remain useable as sawlogs for up to 15 years. Note that the non-recovered losses under optimistic assumptions are continuing to rise at the end of the projection because there is still a substantial quantity of dead wood that has some value but it is not being harvested rapidly enough. In the pessimistic scenario virtually all of the dead wood has completely deteriorated by 2024 and as a result non-recovered losses have begun to level off. The maximum difference between the two sets of assumptions is approximately 320 million $m^3$ and occurs in 2016 when large volumes of dead wood are still deteriorating under pessimistic shelf-life assumptions.

## 4.7 Sensitivity to assumptions about salvage priority

It is not entirely clear how the forest industry will respond to the opportunity to salvage the beetle-killed wood. As described in Section 3.3.4, we model three different assumptions. In the reference scenario we assume that the industry will concentrate salvage activities in areas with the maximum dead volume. It is possible that some licensees will preferentially salvage in areas that meet the minimum criteria for salvage blocks (set here at 50% pine and 50% kill) thus maximizing the live volume harvested during salvage. A "compromise" scenario is one in which the industry maximizes the total volume (both live and dead) that is harvested. At a provincial scale the difference among these scenarios is relatively minor, amounting to only 50 million $m^3$ in non-recovered losses by 2024 (Figure 15). A similar impact on the amount of non-pine volume harvested occurs, rising from 500 million $m^3$ to 550 million $m^3$ (10%) provincially by 2024. However, this varies substantially throughout the province. In management units near the beginning of the infestation with many mixed pine stands there can be a much more dramatic impact on the amount of non-pine harvested. The Merritt TSA provides an instructive example (Figure 16).

# BCMPB v2: Results of year 2 of the project

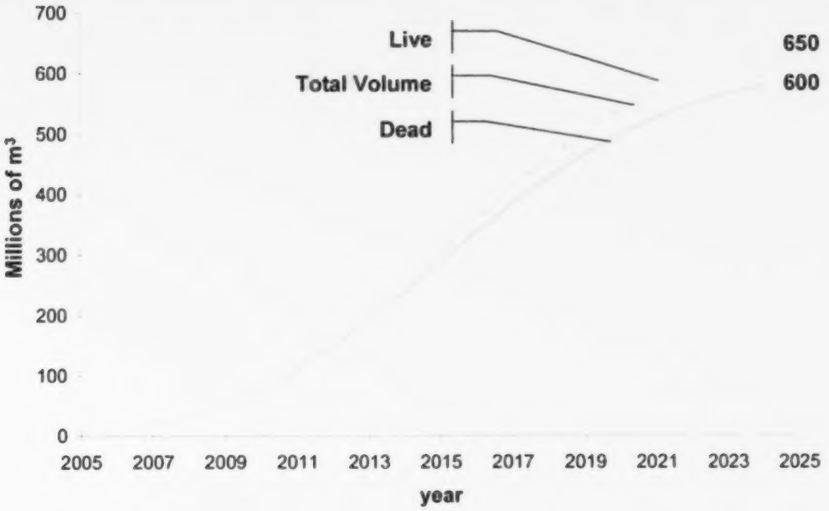

Figure 15. *Cumulative non-recovered losses under three different assumptions about salvage priority employed when harvesting.*

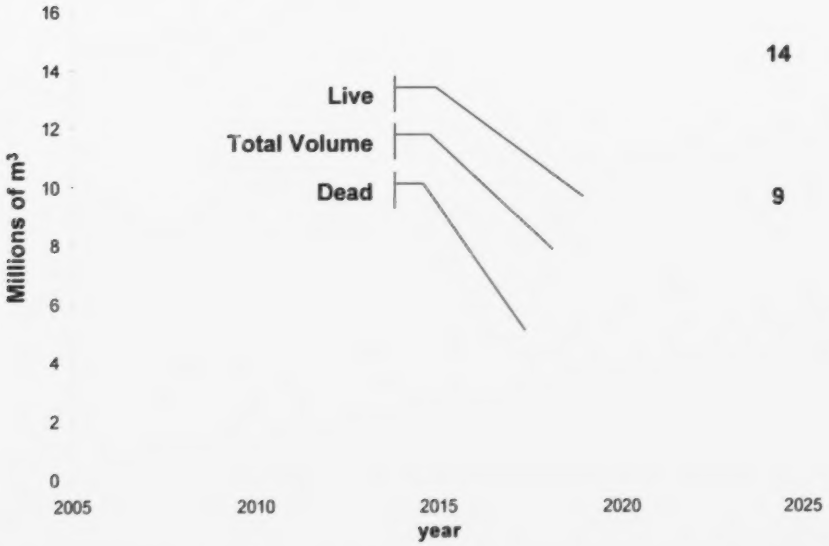

Figure 16. *Cumulative volume of non-pine species harvested in the Merritt TSA under three different assumptions about salvage priority employed when harvesting.*

## 4.8 Implications of alternative harvest levels

We examine the implications of various alternative harvest levels, as described in Section 3.3.5 in an attempt to illustrate the implications on a variety of indicators. It is important to understand that we are not recommending any of the alternative harvest levels nor do we have any expectation that any of the specific alternatives will come to pass.

Figure 17 shows the implications of increasing harvest levels on cumulative non-recovered losses. This figure shows several important implications other than the simple fact that increasing the harvest level decreases the non-recovered losses (by as much as 150 million $m^3$ given the alternatives we examined). The reference scenario has noticeably higher non-recovered losses than the harvest level that includes the expedited increases in AAC for the Lakes, Prince George and Quesnel TSAs. Note also that an immediate increase in the harvest level has the same effect on non-recovered losses as doubling the increase at the peak kill in each unit. The reason is that by increasing the harvest level now we harvest more live pine, primarily in an attempt to control the outbreak. If we wait until after the peak in annual kill in each unit then much of that pine that would have been killed and will begin to deteriorate. In effect, we get behind in our salvaging efforts and we can't catch up because of the deterioration rate.

An important implication of increasing harvest levels is illustrated by a comparison of Figure 18 and Figure 17. For every 0.75 $m^3$ of non-recovered losses that are saved by increasing harvest levels we lose 1.0 $m^3$ of non-pine volume as an "incidental by-catch" of our attempt to ameliorate the non-recovered loss. The reason is that the majority of the susceptible pine occurs in stands where it is mixed with non-pine species (Table 4). By increasing our salvage efforts we also increase our harvest of non-pine volume.

Figure 18 also illustrates that around 2017 the harvest of non-pine species begins to increase dramatically under all harvest levels. Around this time most of the impact of the infestation has been felt for several years. Recall that 80% of the susceptible volume will be killed by 2013 or 2014. By 2017 most of that volume will no longer be useable as sawlogs. Harvesting will switch from salvage to the remaining non-pine volume.

# BCMPB v2: Results of year 2 of the project

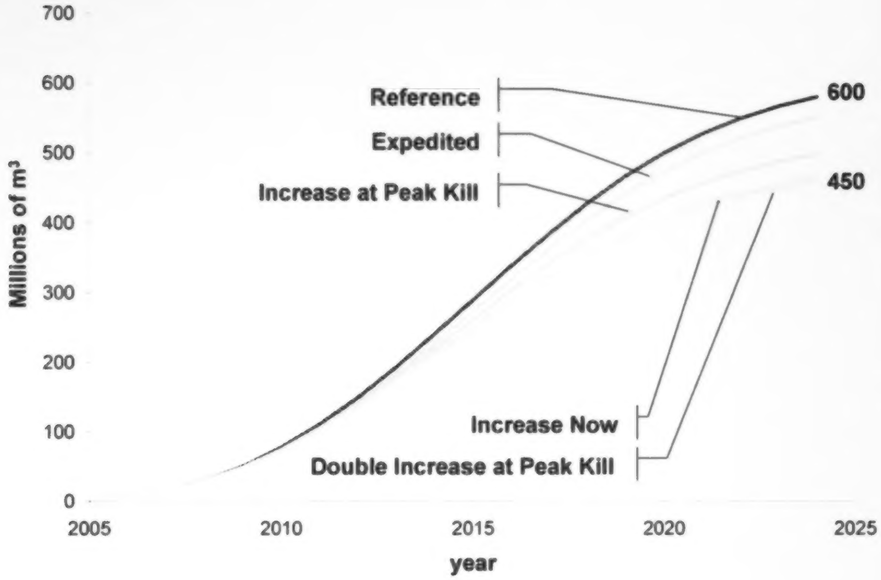

Figure 17. *Cumulative non-recovered losses under various alternative harvest levels.*

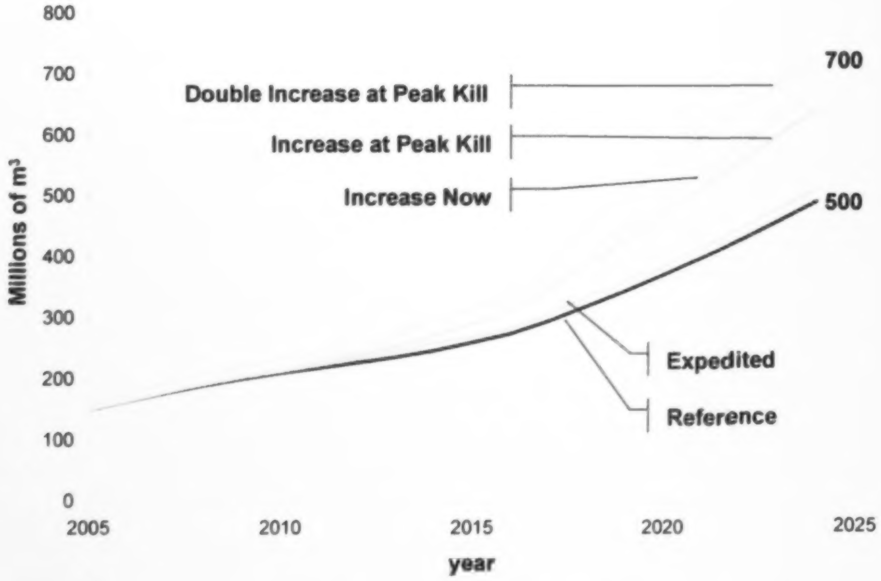

Figure 18. *Cumulative harvest of non-pine volume under various alternative harvest levels.*

## 4.9 Best and worst case scenarios

We modeled best and worst case scenarios with respect to non-recovered losses based on uncertainty about when the infestation will end, what the shelf-life of beetle killed wood will be and how the industry will respond to the opportunity to salvage the beetle killed wood. The specifications for these scenarios and the reference scenario are provided in Table 6. The results, with respect to non-recovered losses, are illustrated in Figure 19. Non-recovered losses differ by 400 million $m^3$ between the best and worst case scenarios. This difference is very asymmetrical with respect to the reference scenario. The best case projects that losses will be half the amount projected by the reference scenario whereas the worst case projects that losses will only be 100 million $m^3$ higher than the reference scenario. The reason for this asymmetry is partly a result of asymmetry in the shelf-life assumptions (as discussed in Section 4.6) and because the assumption about the infestation end in the best case scenario results in lower losses whereas the assumption about the infestation end in the worst is the same as in the reference scenario.

Table 6. *Specification of best and worst case scenarios for non-recovered losses.*

| | Best-Case | Reference | Worst-Case |
|---|---|---|---|
| Shelf-Life | Optimistic | Conservative | Pessimistic |
| Salvage Priority | Dead Volume | Dead Volume | Live Volume |
| Infestation End | Stand Level 66% kill | >95% kill | >95% kill |

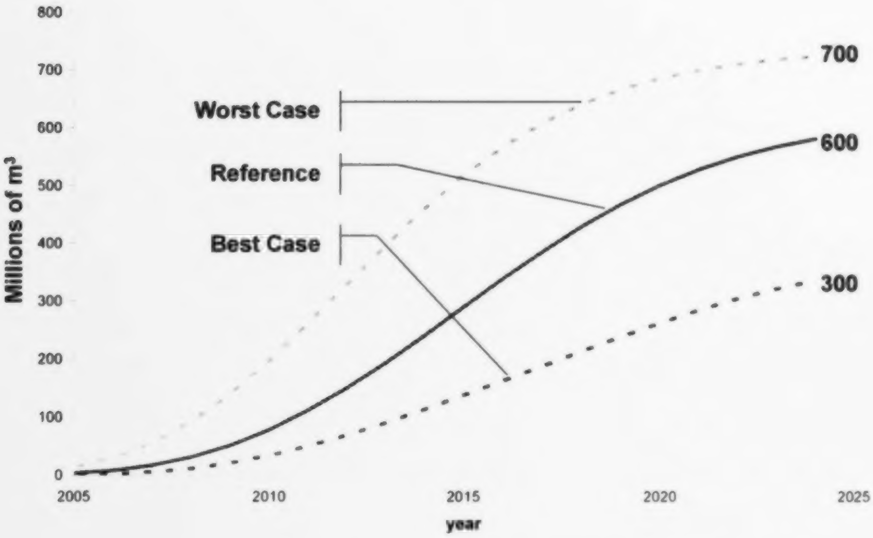

Figure 19. *Cumulative non-recovered losses under best-case, reference and worst-case scenarios.*

## 4.10 Implications for area harvested

Virtually all of the preceding discussion has been about indicators relevant to timber values (wood volume). Most other values (e.g. water quality, wildlife habitat, non-timber forest products) are more closely linked to the area harvested than the volume harvested. In general, as the area harvested increases there is a more significant negative impact on non-timber values.

Our model uses a more-or-less constant target for volume harvested over the projection period for all scenarios except those where the harvest target is explicitly increased (those scenarios discussed in Section 4.8). We modeled 17 separate scenarios where there was no explicit increase in the volume harvest target. On average, the area harvested by those scenarios in 2005 was 150 000 hectares. By 2013 the average area harvested had increased to 200 000 hectares (Figure 20). After 2013 the area harvested begins to decrease and by 2024 less than 150 000 hectares per year are being harvested. Area harvested changes over time because the volume per hectare harvested changes. During the first eight years of the projection the volume per hectare harvested is decreasing because there is an increasing amount of residue (logged non-recovered loss) in the stands. In order to meet the volume harvest target the model has to log additional area. After 2013 the harvesting begins to switch from salvage logging to logging non-pine volume. These areas generally have higher volumes per hectare than the areas with pine so the total harvested area begins to decrease. This effect on area harvested is not intended but it is rather a consequence of the constant volume harvest target and changes in the nature of the forest that is being harvested through time.

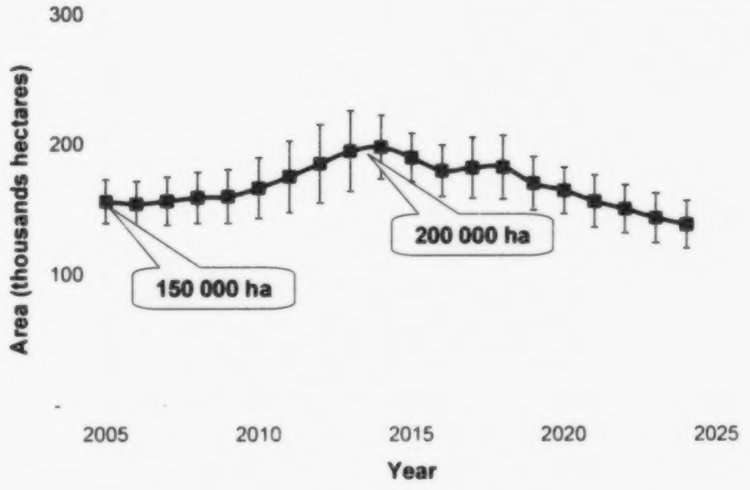

Figure 20. *Mean and standard deviation of annual area harvested in the 21 'pine' TSAs under 17 scenarios not involving explicit increases in harvest levels.*

# 5.0 Conclusions and Next Steps

Our analysis of the current mountain pine beetle outbreak suggests that this outbreak is an order of magnitude larger, both in area infested and volume killed than any previous known outbreak. The largest previous outbreak described by Wood and Unger (1996) was 650 000 hectares in size and occurred on the Chilcotin Plateau between 1930 and 1936. Our analysis indicates that it is most likely that the current outbreak will continue largely unabated until the majority of susceptible host stands in the province are affected. The model has been criticized because we do not include events such as unseasonably cold winter weather that might stop or slow the outbreak. It is true that by excluding the effect of unfavourable weather patterns, we are essentially projecting a worst-case scenario. However, we note that this outbreak is by now so widely distributed that there is not a high probability that the province will experience a severe cold weather event of sufficient spatial extent to affect a significant proportion of the population (Spittlehouse pers. comm.). While there is a wide range of factors that affect mountain pine beetle population dynamics, the general understanding seems to be that once an outbreak has developed, it tends to proceed either until very cold weather causes massive beetle mortality, or until the supply of suitable hosts is depleted (Berryman et al. 1984; Samman and Logan 2000; Wood and Unger 1996). The only possible exception to this pattern appears to be the outbreak in the Flathead in 1977 to 1981, although observations about the collapse of this outbreak are equivocal (Young 1988). The results of this analysis are broadly consistent with conclusions from previous landscape scale analyses in Kamloops, Williams Lake, Morice and Lakes (Fall et al. 2001; 2002; 2003a; 2003b).

The model projects that the peak of the outbreak will occur in 2006 (detected by the provincial aerial overview in 2007)and the annual kill of pine volume, at that time, will be more than 90 million $m^3$ per year. We project that significant volumes (>25 million $m^3$ per year) will continue to be killed until at least 2015. Further we project that pine mortality will not decrease to pre-outbreak levels until after 2020. We stress that these projections represent the worst possible case. It is conceivable that some unforeseen population stopping/slowing event may occur and/or that mortality within stands may not be as high as we project. We modeled various alternate scenarios about when the infestation might end. In addition to the obvious conclusions about the amount of dead pine that will be left on the landscape, the alternate scenarios have different implications with respect to forest management. If the infestation ends abruptly at some point in the future it will be much easier to deal with the consequences than if the infestation kills a lower proportion of the pine in each stand but continues to kill pine for the foreseeable future. We note significant differences in the amount of residue (logged non-recovered losses) that the forest industry will have to deal with under these two different possibilities. We should begin now to systematically assess the levels of mortality being caused by the outbreak in an attempt to distinguish between these two possibilities.

# BCMPB v2: Results of year 2 of the project

We modeled what appeared to be relatively small differences in the shelf-life of beetle killed wood. These differences had dramatic effects on the level of non-recovered losses. At the peak in difference between the optimistic and pessimistic assumptions about shelf-life (in 2016) the non-recovered losses differed by 150% (200 million $m^3$ with optimistic assumptions versus 500 million $m^3$ with pessimistic assumptions). Work is currently being funded by the Mountain Pine Beetle Initiative of the Canadian Forest Service to provide some better estimates of the biological and engineering/manufacturing aspects of shelf-life. That work may resolve some of this uncertainty. However, given that economic factors substantially contribute to the "realized" shelf-life it is entirely conceivable that we will not "know" the shelf-life until after the infestation has subsided and the dead wood has been recovered.

Overall there is such significant uncertainty that estimates of provincial scale non-recovered losses by 2024 vary from 300 million $m^3$ in the best case to 700 million $m^3$ in the worst case. The amount of dead wood that will be available for harvest varies significantly in space and time. Decisions about forest management made at the management unit level can ameliorate non-recovered losses.

We observe that there is an unintended consequence of maintaining a constant volume based harvest target during the infestation. That is, if the volume harvested remains constant, the area harvested increases from 150 000 to 200 000 hectares per year over the first 8 years of the projection and then decreases again during the last 12 years of the projection to less than 150 000 hectares per year. Harvested area changes because the volume per hectare harvested first decreases as more of the dead pine becomes unusable (residue or non recovered loss) and then increases as harvesting switches from salvage logging to the harvesting of non-pine volume.

During the next fiscal year (2005-2006) we intend to improve the model and continue to provide decision support at a provincial scale and management unit scales as appropriate. Improvements to the model will include incorporation of the results of research funded by the Mountain Pine Beetle Initiative of the Canadian Forest Service. At a minimum we hope to do the following:

- Incorporate the work that Dr. Allan Carroll has done under his project titled "Impacts of Climate Change on Range Expansion by the Mountain Pine Beetle". Significant collaboration between one of us (Bill Riel) and Dr. Carroll has allowed us to specifically design BCMPB to enable the incorporation of the spatially explicit climatic suitability surfaces being developed. This will begin in 2005-06 and be finalized in 2006-07.
- Improve some of the parameters related to the large-scale spatial dynamics of the outbreak using the work being conducted by Dr. Allan Carroll ancillary to his project investigating "MPB Outbreak Development: the Endemic-Incipient Transition". We will work closely with Dr. Carroll during 2005-06 to ensure that the work is appropriately incorporated

# BCMPB v2: Results of year 2 of the project

- Improve some of the parameters related to macro-scale and meso-scale dispersal using the results of the Dr. Peter Jackson's work under the project titled "Modeling of MPB Transport and Dispersion using Atmospheric Models". We have already incorporated the basic synoptic climatology work conducted by Dr. Jackson. Starting in 2005-06 and continuing through 2006-07 we intend to refine the synoptic climatology using a higher resolution re-analysis dataset. We also intend to incorporate parameters related to a process-oriented model describing interactions between wind and weather, local topography and the initiation of MPB outbreaks resulting from meso-scale dispersal.
- To the extent possible we will refine the parameters used in our shelf-life model by acquiring any available field data. We anticipate that one of the most important sources will be the shelf-life field work funded by the MPBI and the subsequent analysis of the data by Dr. Kathy Lewis under the project titled "Investigating the Relationship between Timber Recovery, Quality and Time-since-death for Beetle-killed Stands".

We also intend to significantly improve our base model data and the forest management model. We will:

- Obtain a new set of spatial data layers from the Land and Resource Data Warehouse. Our current data will be 3 years out of date this spring.
- Obtain a refined timber harvesting landbase for the province.
- Obtain data required to provide a more complete set of forest cover constraints for the management model. At a minimum we intend to include ungulate winter ranges as a constraint.
- Improve the harvest targets used in the model by modifying those targets based on more realistic assumptions about the changes in harvest targets that may occur over the projection period.
- Incorporate forest stewardship recommendations included in Eng (2004) into the modeling environment. Importantly these recommendations include large cutblocks with high levels of retention.
- Attempt to realistically model the "alternative forest industry" that will emerge as a result of the issuing of forest licenses specifically targeted at salvage logging.

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# Appendix 1

**Spatial Metadata**

http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Appendix1_SpatialMetadata.pdf

# Appendix 2

**Management Sub-model Details**

http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Appendix2_ManagementModel.pdf

# Appendix 3

**MPB Sub-model Details**

http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Appendix3_MPBProjectionModel.pdf

# Appendix 4

**Shelf Life Sub-model Details**

http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Appendix4_ShelfLifeModel.pdf

# Appendix 5

**Reconnaissance Plot Information**

http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Appendix5_ReconnaissancePlots.pdf

# Provincial Level Projection of the Current Mountain Pine Beetle Outbreak:

## Appendix 1: Spatial Metadata

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*Mountain Pine Beetle Initiative of the Canadian Forest Service*
*and the BC Forest Service*

**Marvin Eng, Research Branch, BC Min. of Forests**

**April 2004**

## Purpose of the document

This document specifies the spatial data used by the BCMPB (Provincial Scale Mountain Pine Beetle Projection Model). It also describes in some detail the methods used to generate the spatial data. The document is not intended to provide enough detail to completely reproduce the data. Rather we intend that this appendix could provide enough information for a well informed reader to gain some understanding about how the data was compiled.

## Spatial layers used by the model

Table 1 lists all of the spatial data used by the model. The layers are divided into 5 types:

1. Beetle related information is used to initiate the beetle projection model. All of the layers used by the model are, in fact, calculated from other information, primarily the annual severity of attack data extracted from the provincial aerial overview data. The method of extracting that information is described in the section titled Beetle Population Data.
2. Initiation layers represent the non-recovered losses experience to 2002 and 2003 as a result of the infestation from 1999. Those layers are used to "initiate" the NRLs at the correct level.
3. Forest Cover data was obtained from two separate sources as described in the section titled Forest Cover Data.
4. Management consists of that information required by the forest management submodel. It is data that is used to either direct or constrain harvesting and single tree treatments.
5. Reporting Strata are required to develop the indicator files. Reporting strata do not influence the behaviour of the model. Rather they are used in a post-processing step to "cut" the results by areas of interest to specific clients.

Additional metadata for the spatial layers used by the model and for layers used to create the layers used by the model can be found in BCMPB_SpatialMetadata.xls.

**Table 1. Spatial layers used by the model (BCMPB).**

| Layer Name | Layer Description | Layer Type | Calculated |
|---|---|---|---|
| habitatCo | Beetle habitat | Beetle | Yes |
| svCombine02 | combined severity in 2002 | Beetle | Yes |
| svCombine03 | combined severity in 2003 | Beetle | Yes |
| cumPressure3 | Cummulative beetle pressure in 2002 | Beetle | Yes |
| cumPressure4 | Cummulative beetle pressure in 2003 | Beetle | Yes |
| cumKill02 | Cummulative percentage of pine killed in 2002 | Beetle | Yes |
| cumKill03 | Cummulative percentage of pine killed in 2003 | Beetle | Yes |
| localPressure3 | local beetle pressure 2002 | Beetle | Yes |
| localPressure4 | local beetle pressure 2003 | Beetle | Yes |

| | | | |
|---|---|---|---|
| timeSinceKill02 | Time since the last beetle kill in 2002 | Beetle | Yes |
| timeSinceKill03 | Time since the last beetle kill in 2003 | Beetle | Yes |
| nrl02 | Non recovered losses in 2002 | Initiation | Yes |
| nrl03 | Non recovered losses in 2003 | Initiation | Yes |
| pcpClassCo | Percent pine classified | Forest Cover | Yes |
| ageCo | age of the forest | Forest Cover | No |
| itg_b | Inventory type groups | Forest Cover | No |
| pcpCo | Percent pine | Forest Cover | No |
| spc_pine_b | Pine species | Forest Cover | No |
| sindex_b | Site index | Forest Cover | No |
| vol_b | Total timber volume | Forest Cover | No |
| volpine_b | Volume of pine | Forest Cover | No |
| Dist2Road | Distance to roads | Management | Yes |
| NearestRoadLoc | Location of the nearest road | Management | Yes |
| bmu03 | Beetle management unit designation in 2003 | Management | No |
| bmuname | Beetle Management unit id by name | Management | No |
| dem | Digital elevation model | Management | No |
| ebbma03 | Emergency bark beetle management area designations in 2003 | Management | No |
| mgmtunits | Forest management units (TSAs and TFLs) | Management | No |
| thlbtrue | Timber harvesting landbase | Management | No |
| vqo | Visual quality objectives | Management | No |
| rmz2 | Generalized Resource management zones | Reporting Strata | Yes |
| abec_bc | Biogeoclimatic subzone variants | Reporting Strata | No |
| cariherd | Caribou herds | Reporting Strata | No |
| gbearpopn | Grizzly bear populations | Reporting Strata | No |
| lu | Landscape Planning Units | Reporting Strata | No |
| spupl | Pine seed planning units | Reporting Strata | No |
| parks | Provincial and National Parks | Reporting Strata | No |
| provtrue | Provincial land mass | Reporting Strata | No |
| rmz | Resource management zones | Reporting Strata | No |
| spusx | Spruce seed planning units | Reporting Strata | No |

## Beetle Population Data

The annual kill for each year from 1999 to 2003 was obtained from the Provincial Aerial Overview ("the overview") data. The method involved overlaying a 1200 meter grid on the polygonal and spot data from the overview. The area affected in each grid cell was then calculated as the area in a severity class multiplied by the mid-point of the kill estimate for that severity class. For the spot data the area of the spot was used. The following ARC/INFO macro shows how the calculations were performed for one year of the overview data. A description of how the 1200 meter grid data was converted to a 400 meter grids is provided in Appendix 3.

```
/* Create overlay of fishnet and points and polygon data
/* and summary tables of points and polygon data
Precision Double Highest
&echo &brief

/* point overlay
 Identity C:\Work\mpb\indata\mofairoverdataraw\prvspot03
C:\Work\mpb\indata\mpbpopn\fishnet C:\Work\MPB\InData\MPBPopn\spot03 Point #
Join

/* point statistics
Statistics C:\Work\mpb\indata\mpbpopn\spot03.pat
C:\Work\MPB\InData\MPBPopn\spot03.freq fishnet#
Sum NUM_TREES
Sum spot_area
end

/* point output
infodbase spot03.freq spot03

/* polygon overlays and calculations
Identity C:\Work\mpb\indata\mofairoverdataraw\prvpoly03
C:\Work\mpb\indata\mpbpopn\fishnet C:\Work\MPB\InData\MPBPopn\poly03 Poly
0.000001 Join
additem poly03.pat poly03.pat perckill 4 4 f 2
additem poly03.pat poly03.pat areakill 8 18 f 5
tables
        select poly03.pat
        reselect severity = 'L'
        calc perckill = 0.05
        select poly03.pat
        reselect severity = 'M'
        calc perckill = 0.20
        select poly03.pat
        reselect severity = 'S'
        calc perckill = 0.50
        select poly03.pat
        reselect severity = ‘V’
        calc perckill = 0.50

        select poly03.pat
        calc areakill = area * perckill
quit


/* polygon statistics
STATISTICS C:\Work\mpb\indata\mpbpopn\poly03.pat
C:\Work\MPB\InData\MPBPopn\poly03.freq FISHNET#
Sum AREA
Sum PERCKILL
Sum AREAKILL
end


/* polygon output
infodbase poly03.freq poly03

/* gets the area killed into an attribute in fishnet.  adds poly and spot area
/* add area killed attribute
/* This is the second time around so we don't need to add additem fishnet.pat fishnet.pat
areakill03 8 18 f 5

/* create indices for more rapid calculations
indexitem fishnet.pat fishnet#

indexitem poly03.freq fishnet#
indexitem spot03.freq fishnet#
/*  Create relates
relate add rpoly03 poly03.freq info fishnet# fishnet# linear ro
relate add rspot03 spot03.freq info fishnet# fishnet# linear ro
/* Do calculations sum-spot_area is in ha so is multipled by 5000 to give 50% attack in
meters squared
/* this give equivalent units to sum-areakill
tables
select fishnet.pat
 calc areakill03 = 0
 calc areakill03 = rpoly03//sum-areakill
 calc areakill03 = areakill03 + ( rspot03//sum-spot_area * 5000 )
quit
```

## Forest Cover Data

All of the forest cover data used in the model was obtained from two separate sources. The majority of the data, for all area managed as Timber Supply Areas was obtained from the provincial "corporate" spatial database known as the Land and Resource Data Warehouse (LRDW). The methods of obtaining the information and converting it to 400 meter grids are described below. For some areas of the province the LRDW does not contain any data. These primarily are:

- large areas of private land on Vancouver Island and the in the southern east Kootenays;
- most Tree Farm Licenses (TFLs); and
- some large parks created prior to the advent of digital forest cover mapping.

Data for the parks was made available as a result of the work done on the 1994 Forest and Range Recreation Resource Analysis. The authors obtained the 1956 continuous forest cover mapping for the missing parks. The information was digitized, the labels were converted to modern formats and the data on age and volume was projected to the current date. Some updates for major depletions were incorporated through visual interpretation of satellite imagery. Data for TFLs was obtained by the Crown in 1996 as part of a project that was designed to complete the forest cover mapping for the province. Unfortunately there is no available source of forest cover data for the private land. The TFL and Parks data was incorporated into

The LRDW Forest Cover data were extracted in 1:250,000 NTS map sheet "blocks" from the Ministry of Sustainable Resource Management's Land and Resource Data Warehouse using Arc/Info. Each of the resulting 1:250,000 Arc/Info "Coverages" were populated with the forest stand information required for this study. Percent Pine and Pine Species were also calculated for each forest stand. Coverages containing only a single forest inventory theme were created (e.g. stand age) for each map sheet. This was done so that the coverages reflected the spatial distribution the inventory theme rather than the spatial distribution of the stands. Each 1:250,000 forest inventory theme coverage was converted to an Arc/Info raster "Grid" using a raster resolution of 400 m by 400 m. For each forest inventory theme, the 1:250,000 raster grids were joined together to create a single raster grid which covered the entire province. Each province-wide grid was converted to Arc/Info ASCII format for subsequent use in SELES.

A similar process was used to extract the data for TFLs and Parks from the "continuous forest cover dataset". The two datasets were then combined such that if LRDW data was available it was used otherwise the continuous forest cover data was used.

## Management (forest) data

The following management data layers were obtained directly from their sources and simply converted to a 400 meter grid

- bmu03
- bmuname

- dem
- ebbma03
- mgmtunits
- vqo

The road related layers (Dist2Road and NearestRoadLoc) were calculated based on the location of roads as represented in the LRDW. Any road related feature code was used to indicate the presence of a road.

Development of a spatially explicit timber harvesting landbase (THLB) (thlbtrue) for the entire province was a non-trivial task. There were 3 principal problems:

1. A large quantity of data in varying formats had to be processed;
2. All the expressions of percent inclusion in the THLB had to be converted to 100% in or 100% out of the THLB; and
3. THLB for the Tree Farm Licenses is not readily available and had to be estimated.

The initial input data was provided primarily as district files either in ARC coverage (vector) and ARC grid (raster) format. Depending on the area, in some instances there was areas of overlap between data sets. One or more attributes relating to the THLB were present in all the data sets and all data sets had a attribute that contained the THLB inclusion factor (in percent). It is this attribute that was used to create the provincial THLB grid. Most, but not all of the data sets have an attribute that classified the THLB by type of inclusion where:

- "X" = outside THLB
- "N" = within THLB but zero percent inclusion
- "P" = partial inclusion in THLB
- "C" = one hundred percent inclusion in THLB

Since only the percentage of inclusion within the THLB was of interest, the above inclusion classification was not retained in the final provincial (THLB_BC) data set.

The procedure for creating the THLB grid from the input data is outlined below:

1. If the data set was in ARC coverage format, the dataset all items except those relating to the THLB were dropped, sliver polygons were removed if necessary and the coverage was dissolved with the #ALL option in ARC. In some cases this 'clean-up' greatly reduced the size of the dataset.
2. Coverages were converted to GRID with a 50 metre x 50 metre cell size using the POLYGRID command in Arc.
3. Depending on the original data set, areas with an inclusion factor value of zero OR a 'no-data' could be either: a) areas outside the THLB, b)areas within the THLB but with a zero inclusion factor or c) areas outside the spatial extent of the original coverage. All 'no data' areas of each GRID were converted to zero using the CON and ISNULL commands in GRID. This was done to ensure all areas within the BLOCKMEAN processing window were used in the computation. This provided consistency with how each dataset was processed (as zero and no data values could mean the same or different things)

and to prevent overestimating the percentage of THLB inclusion which occurs when areas with 0 percent inclusion have a 'no-data' value (as they are then excluded from determining the mean value in BLOCKMEAN).

4. Each 50 metre grid was aggregated into a grid with a 400 metre by 400 metre cell size using the BLOCKMEAN GRID function. Since all ISNULL areas were previously converted to zero, all 50 metre cells within the processing window were used in determining the mean value.
5. All areas with zero value were converted to ISNULL in preparation of the appending process whereby the single grids were appended together to create a provincial dataset. This was done so that where areas of overlap occurred, areas with a zero value from one grid (representing areas outside the original coverage area) did not 'erase' the overlapping areas of another grid during the append process where the inclusion factor was greater than zero
6. The analysis environment was set to a provincial extent. Xmin ymin xmax ymax values were as follows: 270000 330000 1874400 1736400. All individual grids were then appended together to create the final provincial dataset of THLB inclusion. Since the order of input determines the priority in areas of overlap in cases of overlap, those data sets seen as more accurate were appended first. THLB_BC is the final output (400m x 400m, floating point type).

The resulting grid contained a "percent inclusion" in the THLB that was a continuous value from 0 to 1. We converted that to only 0 or 1 by randomly including cells in the THLB based on the percentage inclusion.

The area within a Tree Farm License was place in the THLB if it met all of the following criteria:

- Forested
- Site Index greater than 7
- Not deciduous
- Slope less than 40%
- Elevation less than 1800 meters.

Subsequently an additional 2.5% of the cells in each TFL were removed from the THLB

## Reporting strata

The spatial layers for the reporting strata were obtained directly from the LRDW and simply converted to 400 meter grids.

# Provincial Level Projection of the Current Mountain Pine Beetle Outbreak:

## An
## Overview of the Model (BCMPB) and Results

## Appendix 2. Management Sub-model Details

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**Marvin Eng, Research Branch, BC Min. of Forests**
**Andrew Fall, Gowlland Technologies Ltd.**
**Josie Hughes, Research Consultant**

**April 2005**

The management sub-models include planning, single-tree treatment and harvesting components. The broad objectives of these components are to capture the interaction between human forest management planning and actions, with feedbacks between the forest state, the MPB state and forest management constraints and goals (see Figure 1 in main summary document).

## A2.1 Planning: Inventory Availability

This event performs an inventory analysis each time step. Unlike in a timber supply model, volume/ha is not updated by the model, but is rather an input grid. That is, the model tracks depletion of growing stock from harvesting and MPB, but not accrual of new volume due to stand aging. Given the short time horizon of model runs, this helps reduce model complexity.

We define *merchantable* stands as those with at least 150 m3/ha. We define *available* stands as merchantable stands that are within 2km of road access, and in zones not exceeding amount of young to meet visual quality objectives. The visual quality constraints applied are shown in Table 1, and were met within each landscape unit. These were estimated from values used in some TSAs and revised from values used in year 1 based on sensitivity analysis results. We plan further sensitivity analysis assessments these values in the upcoming year.

Table 1. Visual quality objectives applied by BCMPB

| VQO Type | Young age | Max. young |
|---|---|---|
| IRM | 12 years | 25% |
| Maximum Modification | 20 years | 25% |
| Modification | 20 years | 25% |
| Partial Retention | 20 years | 15% |
| Retention | 20 years | 5% |
| Preservation | 20 years | 1% |

Cells that may potentially be harvested as salvage are also identified. A cell may be classified as "salvage" if three criteria are met:

(i) There is sufficient pine in the cell (percent pine is $\geq 50\%$)
(ii) There is sufficient beetle mortality in the cell (percent of the pine that is killed is $\geq 50\%$)
(iii) There is sufficient merchantable sawlog volume in the standing dead wood and residual live wood (sawlog yield is $\geq 100\text{m}^3$).

The first criterion ensures that the amount of non-pine "by-catch" is limited. The second ensures that the stand has sufficient cumulative attack to be classified as a salvage cell and to limit "by-catch" of live pine. The last criterion ensures that the stand is still economic to harvest. Note that, since a cell may experience multiple years of attack, it is possible for a cell to meet both the requirements for "green" harvest and for salvage. In this case, the logging sub-model will select the classification with the highest preference, which depends on the type of the BMU in which the cell resides.

## A2.2 Planning: BMU rating

The second key task of this sub-model is to establish beetle management unit (BMU) types: monitor, suppression, holding action or salvage. For each BMU, the detectable area attacked as computed, and stratified by within/outside THLB and endemic/non-endemic, and an "outbreak level index" (*BMU rating)* was computed as:

$$\text{(Area with endemic MPB state)} + \text{(Area with MPB state} > \text{endemic)}^2$$

The area of non-endemic MPB attack was squared is to place more weight on heavier attack levels, but the rating otherwise corresponds to increasing levels of MPB activity. The list of BMUs is then sorted according to the index, with smallest values first and BMUs are processed sequentially in this order. BMUs with no detectable MPB are processed first and assigned a *monitor* type. If the single-tree budget and AAC budget (after reductions for previously processed BMUs) is capable of addressing at least 80% of the "treatable" attack (i.e. all attack in the THLB plus endemic outside the THLB can be treated with harvesting and/or single-tree treatments), then a BMU is assigned a *suppression* type. Otherwise, if the AAC budget (after reductions for previously processed BMUs) is capable of addressing at least 50% of the "treatable" attack (i.e. attack in the THLB can be treated with harvesting), then a BMU is assigned a *holding action* type . Finally, unassigned BMUs are assigned a *salvage* type. Once a BMU is assigned a *salvage* type in a given year, it remains that type for the remainder of the simulation.

## A2.3 Operations: Harvesting

This event performs forest harvesting in some portion of available cells. It applies target AACs simultaneously in each TSA/TFL in the province. Each management unit is processed independently, and so the model can be described from the perspective of a single unit. The harvest target for each management unit can be specified using a volume-base ($m^3$/year) or an area-based AAC (ha/year) to harvest within the THLB. All main analyses in year 2 applied a volume-based harvest, with base values shown in Table 2.

Table 2. Base harvest levels (in 1000's of $m^3$ ) for each management unit applied by BCMPB up to year 2013, specified as an annual volume ($m^3$) to harvest.

| MgmtUnit | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 100MileHouse | 1334 | 1334 | 1334 | 1334 | 1334 | 1334 | 1334 | 1334 | 1334 | 1334 | 1334 |
| Arrow | 550 | 550 | 550 | 550 | 550 | 495 | 495 | 495 | 495 | 495 | 495 |
| Arrowsmith | 392 | 392 | 392 | 392 | 392 | 392 | 392 | 350 | 350 | 350 | 350 |
| Boundary | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 700 |
| Bulkley | 882 | 882 | 882 | 882 | 882 | 787 | 787 | 787 | 787 | 787 | 787 |
| Cassiar | 305 | 305 | 305 | 305 | 305 | 305 | 305 | 305 | 305 | 305 | 305 |
| Cranberry | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 |
| Cranbrook | 838 | 941 | 941 | 941 | 941 | 941 | 941 | 941 | 941 | 941 | 941 |
| DawsonCreek | 1860 | 1860 | 1860 | 1860 | 1860 | 1860 | 1860 | 1860 | 1860 | 1860 | 1860 |
| FortNelson | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fraser | 1079 | 1080 | 1080 | 1080 | 985 | 985 | 985 | 985 | 985 | 985 | 985 |
| FtStJames | 2482 | 2482 | 2482 | 2482 | 2482 | 2482 | 2482 | 2482 | 2482 | 2482 | 2482 |
| FtStJohn | 2115 | 2115 | 2115 | 2115 | 2115 | 2115 | 2115 | 2115 | 2115 | 2115 | 2115 |
| Golden | 485 | 485 | 485 | 485 | 485 | 485 | 485 | 485 | 485 | 485 | 485 |
| Invermere | 537 | 582 | 582 | 582 | 582 | 582 | 523 | 523 | 523 | 523 | 523 |
| Kalum | 437 | 437 | 437 | 437 | 437 | 437 | 437 | 437 | 437 | 437 | 437 |
| Kamloops | 4353 | 4353 | 4353 | 4353 | 4353 | 4024 | 4024 | 4024 | 4024 | 4024 | 4024 |
| Kingcome | 1204 | 1240 | 1240 | 1240 | 1115 | 1115 | 1115 | 1115 | 1115 | 1115 | 1115 |
| Kispiox | 977 | 977 | 977 | 977 | 977 | 977 | 879 | 879 | 879 | 879 | 879 |
| KootenayLake | 681 | 681 | 681 | 681 | 681 | 681 | 681 | 681 | 681 | 681 | 681 |
| Lakes | 2962 | 2962 | 2962 | 2962 | 2962 | 2962 | 2962 | 2962 | 2962 | 2962 | 2962 |
| Lillooet | 636 | 636 | 636 | 636 | 636 | 636 | 636 | 636 | 636 | 636 | 636 |
| Mackenzie | 3050 | 3050 | 3050 | 3050 | 3050 | 3050 | 3050 | 3050 | 3050 | 3050 | 3050 |
| Merritt | 1508 | 1358 | 1358 | 1358 | 1358 | 1358 | 1358 | 1358 | 1358 | 1358 | 1358 |
| MidCoast | 795 | 795 | 795 | 795 | 795 | 795 | 795 | 795 | 795 | 795 | 795 |
| Morice | 1961 | 1961 | 1961 | 1961 | 1961 | 1961 | 1961 | 1961 | 1961 | 1961 | 1961 |
| Nass | 865 | 865 | 865 | 865 | 865 | 776 | 776 | 776 | 776 | 776 | 776 |
| NorthCoast | 547 | 547 | 547 | 547 | 547 | 547 | 547 | 547 | 547 | 547 | 547 |
| Okanagan | 2655 | 2655 | 2655 | 2655 | 2655 | 2655 | 2655 | 2655 | 2655 | 2655 | 2655 |
| PrinceGeorge | 4385 | 4385 | 4385 | 4385 | 4385 | 4385 | 4385 | 4385 | 4385 | 4385 | 4385 |
| QueenCharlotte | 361 | 361 | 361 | 361 | 361 | 361 | 361 | 361 | 361 | 361 | 361 |
| Quesnel | 3248 | 3248 | 3248 | 3248 | 3248 | 3248 | 3248 | 3248 | 3248 | 3248 | 3248 |
| Revelstoke | 230 | 230 | 230 | 230 | 230 | 230 | 230 | 230 | 230 | 230 | 230 |
| RobsonValley | 602 | 602 | 602 | 602 | 602 | 542 | 542 | 542 | 542 | 542 | 542 |
| Soo | 503 | 503 | 503 | 503 | 503 | 503 | 503 | 503 | 503 | 503 | 503 |
| Strathcona | 1278 | 1278 | 1278 | 1278 | 1278 | 1125 | 1125 | 1125 | 1125 | 1125 | 1125 |
| SunshineCoast | 1143 | 1143 | 1143 | 1143 | 1143 | 1143 | 1143 | 1143 | 1143 | 1143 | 1143 |
| Vanderhoof | 5377 | 5377 | 5377 | 5377 | 5377 | 5377 | 5377 | 5377 | 5377 | 5377 | 5377 |
| WilliamsLake | 2923 | 2923 | 2923 | 2923 | 2923 | 2923 | 2923 | 2923 | 2923 | 2923 | 2923 |
| TFL1 | 611 | 611 | 611 | 611 | 611 | 611 | 611 | 611 | 611 | 611 | 611 |
| TFL10 | 171 | 171 | 171 | 171 | 171 | 171 | 171 | 171 | 171 | 171 | 171 |
| TFL14 | 160 | 160 | 160 | 160 | 160 | 160 | 160 | 160 | 145 | 145 | 145 |
| TFL15 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 65 | 65 | 65 |
| TFL18 | 178 | 178 | 178 | 178 | 178 | 178 | 178 | 152 | 152 | 152 | 152 |
| TFL19 | 940 | 940 | 940 | 904 | 904 | 904 | 904 | 904 | 869 | 869 | 869 |
| TFL23 | 680 | 680 | 680 | 680 | 680 | 680 | 680 | 680 | 680 | 680 | 680 |
| TFL25 | 557 | 557 | 514 | 514 | 514 | 514 | 514 | 514 | 514 | 514 | 514 |
| TFL26 | 45 | 45 | 45 | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 |
| TFL3 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| TFL30 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 315 | 315 | 315 |
| TFL33 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 30 | 30 | 30 |
| TFL35 | 126 | 326 | 326 | 326 | 326 | 326 | 326 | 326 | 326 | 326 | 326 |
| TFL37 | 1068 | 1068 | 1068 | 1068 | 1068 | 1068 | 1049 | 1049 | 1049 | 1049 | 1049 |
| TFL38 | 251 | 251 | 251 | 251 | 251 | 233 | 233 | 233 | 233 | 233 | 233 |
| TFL39 | 3547 | 3547 | 3547 | 3547 | 3547 | 3547 | 3547 | 3547 | 3502 | 3502 | 3502 |
| TFL41 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 |
| TFL42 | 160 | 160 | 160 | 160 | 160 | 160 | 160 | 160 | 160 | 160 | 160 |
| TFL43 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| TFL44 | 1327 | 1327 | 1327 | 1288 | 1288 | 1288 | 1288 | 1288 | 1249 | 1249 | 1249 |
| TFL45 | 208 | 208 | 208 | 208 | 208 | 208 | 208 | 208 | 208 | 208 | 208 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| TFL46 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 |
| TFL47 | 780 | 780 | 780 | 780 | 780 | 780 | 780 | 780 | 780 | 780 | 780 |
| TFL48 | 580 | 580 | 580 | 580 | 580 | 580 | 580 | 580 | 580 | 580 | 580 |
| TFL49 | 380 | 380 | 380 | 380 | 380 | 380 | 380 | 380 | 380 | 380 | 380 |
| TFL5 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 |
| TFL52 | 570 | 570 | 570 | 570 | 570 | 570 | 570 | 570 | 570 | 570 | 570 |
| TFL53 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 |
| TFL54 | 76 | 76 | 76 | 76 | 76 | 76 | 76 | 76 | 76 | 76 | 76 |
| TFL55 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 81 | 81 | 81 |
| TFL56 | 100 | 101 | 101 | 101 | 101 | 101 | 99 | 99 | 99 | 99 | 99 |
| TFL57 | 124 | 124 | 124 | 124 | 124 | 124 | 124 | 124 | 124 | 124 | 124 |
| TFL6 | 1737 | 1737 | 1737 | 1737 | 1644 | 1644 | 1644 | 1728 | 1728 | 1728 | 1728 |
| TFL8 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 |

Each model year, the target AAC provides a "beetle management potential". How this is allocated across a unit depends on the BMU ratings, MPB state, stand ages/volumes and salvage volumes, and is designed to capture the fundamentals of bark beetle management (MOF and BCE 1995). The available cells in the unit are stratified into groups based on BMU rating and MPB outbreak state, and processed according to a priority order. The following described the strata, from highest to lowest priority within a management unit:

- Low and moderate MPB in suppression BMUs: focuses harvesting on leading edge attack.
- Endemic and severe MPB in suppression BMUs: focuses harvesting on other MPB attack in suppression BMUs.
- Low and moderate MPB in holding action BMUs: focuses harvesting on leading edge attack
- Severe MPB in holding action BMUs: focuses harvesting on high populations
- Salvage in salvage BMUs: areas that meet salvage criteria described in section A2.1.
- Moderate and severe MPB in salvage BMUs: focuses harvesting on areas likely to result in substantial salvage
- Salvage in other BMUs, and low and endemic MPB in salvage BMUs: remaining "mop-up" classes
- Green harvest (no MPB) in any BMU: regular green harvest

All available cells within a stratum are harvested before any cells in subsequent strata. Within each stratum, ordering is according to stand age (linearly increase with age relative to average minimum harvest age of 60 year for pine leading stands and 120 years for other stands), distance to roads (linear decline with distance) or salvagable volume (linear increase with volume or proportion), depending on BMU type and scenario parameters (i.e. cells classified as salvage base preference on the live plus standing dead sawlog quality volume, while other stands use age). In units with no MPB (i.e. all BMUs are *monitor* types), harvesting will be "green harvest", and hence according to "oldest-first, nearest to road". In management units with a mixture of BMU types and MPB states, the actual allocation of harvesting will primarily focus on reducing populations (i.e. using MPB state), followed by salvage. In management units dominated by salvage BMU types, the default harvesting strategy will be "highest salvage-volume first, nearest to road".

In some scenarios, the preference ordering above was modified. For example, to set up an "early switch to salvage" scenario, the preference for salvage blocks can be increased. If a cell is available for harvest according to both green criteria (i.e. min. harvest age, VQO) and salvage criteria (i.e. min. percent pine, min percent killed and min. volume yield), then the class with the highest preference will be applied. In addition, for salvage cells, parameters can control the relative weight of live and sawlog volume in determining preference (e.g. preference could be based entirely on standing dead wood, live wood, or some combination, depending on scenario objectives; the default focus is on dead wood volume).

The default cutblock size was 16-32ha (1-2 cells), based on a spatial assessment of recent block sizes in different regions of the province, and on the bark beetle regulations. Blocks are placed sequentially within a management unit until the harvest target is met.

Where blocks are placed, volume (green and salvage) is recuperated, harvest indicators are updated, MPB state is reset to "no MPB" (i.e. the model effectively assumes 100% efficacy), stand age is reset to 0, and visual targets are updated. In addition, this sub-model explicitly connects cutblocks to the main road network by adding a link from the first cell harvested in a block to the nearest existing road. It then updates a map indicating the distance from each cell to the nearest existing road. This step permits estimation of the amount of road constructed under a given management regime, and influences accessibility in the future.

### A2.4 Operations: Single-Tree Treatments

This sub-model simulates fell and burn and MSMA treatment methods in each *suppression* BMU of the province simultaneously. First the provincial budget is allocated among *suppression* BMUs proportionally based on level of endemic MPB state. That is, if a suppression BMU has x% of the total endemic cells of all suppression BMUs, then it will receive x% of the single-tree treatment budget. Given a single-tree treatment allocation, the remainder of the model description can be cast from the perspective of a single BMU. Single-tree treatments are generally applied in inaccessible areas (up to 5km from a road) or areas with low (endemic and some low MPB state) beetle populations. These treatments are applied to individual cells, and the volume is not recovered. The model assumes that the MPB state is reduced by one level (i.e. endemic state becomes "no MBP", while low becomes endemic).

# Provincial-Level Projection of the Current Mountain Pine Beetle Outbreak:

## An

## Overview of the Model (BCMPBv.2)

## and

## Results of Year 2 of the Project

## Appendix 3. Mountain Pine Beetle Projection

*Supported by the*
*Mountain Pine Beetle Initiative of the Canadian Forest Service*
*and the BC Forest Service*

March 2005

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## 1 Data Preparation Steps

### 1.1 Get age and percent pine from forest cover database

Spatial layers representing forest age in years and percentage of the volume of timber that is contributed by pine (of any species) were extracted from the provincial digital forest cover map, also known as the Land and Resource Data Warehouse (http://srmgww.bcgov/bisd/imb/ds/projects/idw/index.html). Only data available in the LRDW was used to parameterize the beetle model. There is no data in the LRDW for Tree Farm Licenses and some of the large old parks. Forest cover data are available for these areas, and was used when model projections were made, but the quality and currency of this data is not suitable for creating parameter estimates.

Forest age is available directly as a field in the LRDW database. The percentage of pine was determined by identifying which, if any, of the six species in the database were pine and then summing the associated species percent fields. In general, only one pine species was present in a stand although there were a surprising number of exceptions to this rule.

The resulting information was extracted as ARC/INFO polygon coverages and generalized on age and percent pine. The coverages were then converted to grids with a 16 hectare cell size using the ARC POLYGRID command. This command works by intersecting the polygon layer with a 16-hectare grid and determining attribute of the largest resulting polygon for each grid cell. The entire grid cell is then assigned that attribute.

### 1.2 Address data inconsistencies

A number of inconsistencies can be found in the forest cover information. These include areas where there is pine volume, but no age or percent pine, or areas with age or percent pine, but no pine volume. The beetle projection model is driven by percent pine and age, but we often report results in volume. Areas with pine volume but no age and/or percent pine will be effectively immune from beetles in our model. We would prefer not to worry about whether our results are confounded by illogical data, so we remedy those cases where pine volume is rendered immune. We note other types of errors, but do not do anything about them.

| Condition 1 | Condition 2 | number of cases | percent of cases | action |
|---|---|---|---|---|
| vol < volpine | | 0 | 0.000 | none |
| vol = 0 | age > 0 | 1016554 | 27.812 | none |
| vol = 0 | age > 20 | 827978 | 22.652 | none |
| vol = 0 | age > 40 | 695016 | 19.015 | none |
| volpine = 0 | pcp > 0 | 402182 | 11.003 | none |
| %pine = 0 | volpine > 0 | 1373 | 0.038 | volpine = 0 |
| age = 0 | volpine > 0 | 137 | 0.004 | volpine = 0 |
| age = 0 | vol > 0 | 8144 | 0.223 | vol = 0 |
| age > -1 | %pine > -1 | 3655157 | 100.000 | |

Table 1: Inconsistencies in the forest cover data, and remedies applied, if any.

### 1.3 Classify habitat types

We constrain beetles to occur only in areas of suitable climate with some pine component. The pine must also be greater than 60 years old, but stand age is a dynamic layer in our projection model, so we include this factor as a separate constraint, rather than recalculating the habitat suitability map each year. Thus, we classify each 400-metre cell into one of 6 suitability types according to the following scheme:

If no forest cover data is available (TFL's and Parks), then:

Suitability Type = **No Data**

Otherwise, if data indicates no forest cover (age or percent pine value of –1, indicating lakes, rocks, ice, etc), then:

Suitability Type = **No Forest**

Otherwise, if climate is unsuitable, and percent pine is greater than 0, then:

Suitability Type = **Unsuitable Climate, With Pine**

Otherwise, if climate is unsuitable, then:

```
    Suitability Type = Unsuitable Climate, No Pine
Otherwise, if there is no pine present, then:
    Suitability Type = Suitable Climate, No Pine
Otherwise, forest is suitable for beetles:
    Suitability Type = Suitable
```

We define climatic suitability broadly by biogeoclimatic zone. Areas within the following biogeoclimatic zones are considered suitable:

- BG, ESSF, ICH, IDF, MS, PP, SBPS, SBS

For reference, zones deemed unsuitable are:

- AT, BWBS, CDF, CWH, MH, SWB

We further classify suitable habitat into discrete age and percent pine classes. We begin with 20-year age classes, running from 80 (61-80 years) through to 240 (>220 years). Percent pine is classified into 25 percent intervals – the 1-25% class includes areas with 1-25 percent pine, and so on. We separate areas labeled as 100% pine into a class of their own, in part because so much of the landscape falls into this one category, and in part because areas of 100% pine appeared last year to be less heavily infested by beetles that areas which are 76-99% pine. This result is counter to out expectation, and we wish to retain a distinct 100% infestation class in order to check later whether the lower infestation rate in these stands remains when other factors are taken into account, and recent data is added to the model.

When classifying age and percent pine, there are a number of issues for us to consider. First, and most minimally, the amount of forest in each class must be large enough that we can reasonably assume the probabilities we observe are not just an artifact of small sample sizes. Beyond this, we must keep in mind that categories will be further divided by other factors including infestation history and the number of beetles in neighboring regions. With so many important factors, and so many possible categories of each factor, we run a significant risk of over specifying this model. In general, we should retain the minimum possible number of categories at each stage of model development.

### 1.4 Assign beetle infested area to suitable habitat

If we accept the unprocessed aerial overview survey at face value, we find that it is not uncommon for beetles to occur in unsuitable areas, including lakes and rivers well as forested area without pine. It is also common for the percentage of trees infested in a stand to be greater than the percentage of trees that are pine in that stand. Both these situations are impossible, and so indicate errors in either the forest cover data or the beetle mapping. No doubt both data sets contain significant errors, but it is our view that the forest cover database is more reliable than the aerial overview survey data, so we assume that beetles mapped in unsuitable areas indicate an error in the survey data, not in our assessment of habitat suitability.

There are three main types of errors that may occur in the beetle survey data:

- The infestation extent and the number of trees killed within that extent may be correct, but the spatial location may be wrong. We expect this occurs most often when observers are mapping small beetle spots, where it is easy to see that beetles have killed a few trees in a small area, but also easy to get the location of this area slightly wrong. In this case, the beetles mapped do exist, but actually belong in nearby susceptible habitat.
- The infestation extent may be wrong. We expect this occurs when mappers are marking large infestations, and might not bother to omit unsuitable forest areas from the larger polygon. In this case, the beetles mapped are not in the wrong location, but simply do no exist, and should be omitted.
- The percentage of trees killed within an infested area may be wrong. We suspect that the percentage killed is the least reliable aspect of the aerial survey data. In part this is because it is easier to see red trees than green ones, and partly because humans are notoriously poor at assessing the quantitative values by eye. In this case, the infestation is in the right place, but the number of beetles is wrong.

Of course, while we can recognize that three types of errors may occur, we cannot easily distinguish which type of error has occurred in a particular case, or how to remedy it.

That said, we do think that some further processing of the aerial overview survey data will render this data more meaningful and useful.

To begin, we assume that the mapped location of an infestation may be up to 600 metres away from where the actual infestation occurred. In any 144 ha area the number of trees infested by beetles will be approximately right, but the data is uninformative about where exactly the infestation occurred within that area. Thus, we begin by laying a 1200 metre by 1200 metre grid over the aerial survey polygon data, and summing the amount of beetle kill within each grid cell.

We then lay this 1200 metre beetle coverage over our more finely resolved (400 metre grid) forest cover information. Before continuing, we consider areas where no forest cover data is available (Suitability Type = No Data). Since we have no forest cover data for these areas, we cannot say whether beetles may occur there or not. We begin by erasing the beetles that fall within these No Data areas.

Within each 1200 by 1200 metre area, we assign remaining beetles to suitable habitat if there is any. We assume that no more trees can be infested than there are susceptible pine trees to infest, so the maximum area infested in any forest cell is equal to the percentage of pine. Subject to this constraint, infested area each 1200 metre cluster is assigned equally among all suitable cells within that cluster. Thus, the infested area assigned to each suitable 400-metre cell is:

$$\text{AreaKilled}_{400} = \text{Min}\left(\frac{\text{AreaKilled}_{1200}}{\text{Number of Suitable Cells}}, \frac{\text{CellArea} * \text{PercentPine}}{100}\right) \quad \text{Eq. 1}$$

where $\text{AreaKilled}_{1200}$ is the total area infested in the 1200 metre cluster, CellArea is the area of the 400-metre cell (160,000 $m^2$).

Once we have assigned infested area to the suitable habitat available, we are often left with beetles that we have no place to put. Assuming that locations designated unsuitable for beetles really are (i.e. the forest cover data is right), we determine that these beetles could not really have existed, and omit them from further analysis. For interest sake, we track the proportion of these beetles that fall into each kind of area (Figure 1). Overall, the amount of infested area that cannot be assigned to suitable habitat ranges from 7 to 20% over the whole province, depending on the year in question.

## 1.5 Classify infestation intensity

Having allocated the area infested by beetles among suitable areas, we assign the infestation at each location to one of 5 broad severity classes:

| | Lower | Upper |
|---|---|---|
| Severe | 0.3 | 1 |
| Moderate | 0.1 | 0.299999 |
| Low | 0.01 | 0.099999 |
| Endemic | 0.000001 | 0.009999 |
| None | 0 | 0 |

Table 2: Proportion of pine affected by beetles according to the aerial overview survey data.

Note that we are concerned with the proportion of pine area that is affected, rather than the proportion of total area. Thus, a cell where 10% of area is infested by beetles that contains only 10% pine will be considered severely affected. This differs from the severity ratings used in the aerial overview survey, which depend on the overall proportion of all trees that are infested.

## 1.6 What does "severe" really mean?

Of the ~900,000 ha that were severely affected by beetles at some point between 1999 and 2002, ~500,000 ha (69%) remained severely affected for at least three years, and 12% remained severely infested for four or five years. According the aerial survey data, more than 30% of susceptible pine is killed in one year of a "severe" infestation. If we assume a mid-value for severe of 50% kill, we effectively claim that up to 250% of susceptible pine has been killed in many areas over the period from 1999 to 2004. It is logically impossible to kill more than 100% of susceptible pine, so less than 50% must have been killed on average in severely infested areas.

As we have noted before, there are two issues confounding percent kill estimates in the provincial overview data. First, observers tend to overestimate the proportion of red in a stand, and second, last year's attack can sometimes be mistaken for current attack. So it is not a surprise that the aerial overview survey tends to overestimate beetle kill, especially when infestations are severe.

It is the most severe infestation class that cause the most problems, and that we suspect is most wrong. In the absence of more guiding information, we have decided leave the other infestation classes as they are. We assume the minimum amount of kill in severely infested areas is 20%, and the average is 30%. Thus, areas can logically remain severe for up to 3 years. We assume that after three years the infestation subsides, and edit the infestation severity maps accordingly. The updated severity classifications are:

| | Lower | "Mid" | Upper |
|---|---|---|---|
| Severe | 0.2 | 0.3 | 1 |
| Moderate | 0.1 | 0.15 | 0.199999 |
| Low | 0.01 | 0.05 | 0.099999 |
| Endemic | 0.000001 | 0.005 | 0.009999 |
| None | 0 | 0 | 0 |

Table 3: Proportion of pine affected by beetles according to our reinterpretation of the aerial survey data, in light of the fact that more than 100% of pine cannot be killed over the extent of an infestation.

### 1.7 Net down to account for harvesting since 1999

Our forest cover data does not take into account some recent harvesting. While we do not know exactly where this logging has occurred, we do know how much of it has happened in each management unit. To make sure we do not give our beetles more opportunities that real beetles will actually have, we wish to account for this incremental logging. We do this by running our logging model from 1999 to 2004. The logging model is constrained to not cut in areas where beetles will be in future, and otherwise follows the rules for management without reference to beetles.

## 2 Projection Model Overview

### 2.1 Basic approach

Our beetle projection is a discrete probability transition model that runs on an annual time step. Each location in each year will be in one of five beetle states, or infestation severity classes -- NoMPB, Endemic, Low, Moderate, or Severe. The probability that a location will be in a given state depends on the conditions at that location in the previous year. The core of the model is a transition probability table with the following general form:

| Conditions at time t | | | | Probability of beetle state, s, at time t + 1 | | | | |
|---|---|---|---|---|---|---|---|---|
| Index (m) | Factor 1 | .. | Factor n | NoMPB | Endemic | Low | Moderate | Severe |
| 1 | $\text{class}_{1,1}$ | .. | $\text{class}_{n,1}$ | $P_{1,\text{NoMPB}}$ | $P_{1,\text{End}}$ | $P_{1,\text{Low}}$ | $P_{1,\text{Mod}}$ | $P_{1,\text{Sev}}$ |
| ... | ... | .. | $\text{class}_{n,1}$ | ... | ... | ... | ... | ... |
| ... | $\text{class}_{1,i}$ | .. | $\text{class}_{n,1}$ | ... | ... | ... | ... | ... |
| ... | $\text{class}_{1,1}$ | .. | $\text{class}_{n,2}$ | ... | ... | ... | ... | ... |
| ... | ... | .. | $\text{class}_{n,2}$ | ... | ... | ... | ... | ... |
| ... | $\text{class}_{1,i}$ | .. | $\text{class}_{n,2}$ | ... | ... | ... | ... | ... |
| ... | ... | .. | ... | ... | ... | ... | ... | ... |
| ... | ... | .. | ... | ... | ... | ... | ... | ... |
| M | $\text{class}_{1,i}$ | .. | $\text{class}_{n,j}$ | $P_{m,\text{NoMPB}}$ | $P_{m,\text{End}}$ | $P_{m,\text{Low}}$ | $P_{m,\text{Mod}}$ | $P_{m,\text{Sev}}$ |

Table 4: General form of the transition probability table that underlies the mountain pine beetle projection model.

Factors affecting the probability of a given beetle state at time t include the beetle state in the previous year, the cumulative amount killed by beetles at that location in all previous years, the age, percentage of pine, and climatic conditions of the stand, and the amount of beetle pressure from nearby infestations. We parameterize the transition table by classifying the conditions at each location in each year of our data (1999 – 2004). Each location will be assigned a class value for each of n factors. The combination of class values constitutes a location type or condition, each of which is assigned a unique index value, m. We then count the number of cases in each condition and the number of times that that a given beetle state follows each condition. The probability of future beetle state s given cell condition m is:

$$P_{m,s} = \frac{\text{Number of Locations}_{m,s}}{\text{Number of Locations}_{m}} \qquad \text{Eq. 2}$$

We have found it conceptually useful to group cell conditions into one four main categories. First, we distinguish between infestations that are already in progress, and those locations where there are not yet any beetles. Locations without beetles are further divided into areas within 1 kilometre of a current infestation, areas near enough to a current infestation to be subject to significant long-distance beetle pressure, and areas so far from current infestations that any beetle activity is likely to due to increases in local beetle populations, rather than immigration of beetles from other areas. We refer to these latter three categories as "local", "long-distance", and "emergent" respectively (Figure 2).

It is worth pausing for a moment here to examine the concept of "beetle pressure" in more detail. It remains a matter of some uncertainty and controversy to how often beetles disperse farther than 1 km, and how much dispersal contributes to infestations in more distant locations. We do not have enough information to settle the question at this time.

What we can say without doubt is that infestations are more likely arise nearer to current infestations than further away from them. This might be either due to beetle dispersal from one location to another, or because locations near to one another tend to be subject to similar weather and climatic conditions that affect the growth of beetle populations. In our conceptual model, we have favoured the dispersal hypothesis over a more environmental approach, largely because we don't have much information about environmental factors.

It is not our intent to gloss over the uncertainty in this area, nor to claim we understand beetle dispersal and the role it plays in infestation spread. Rather, our aim is to do the best job of predicting the pattern we see given the information we have available. We have done our best to include important factors, and being able to recreate the past gives us some comfort that the model is reasonable. But we may have missed some environmental factors that will be crucial for driving future infestation dynamics. We would welcome any input about what these factors might be, especially if accompanied by data we could use to drive an alternative model. In the meantime, our model predicts what might to happen if beetle dispersal pressure, stand age, percentage of pine and current infestation status are the main drivers of outbreak dynamics.

Infestation start model overview

Formally, locations are potential "start" locations if:

- habitat is suitable (percent pine > 0 and bec zone is suitable)
- stand age is greater than 60 years
- no beetles have been in this location before (cumulative kill = 0)

Given that the preceding necessary conditions are met, the probability of an infestation of given severity arising depends on:

- stand age
- local beetle pressure
- long-distance beetle pressure
- percentage of pine in the stand

See Section 3 for explanation of how beetle pressure is calculated. See Section 4 for discussion of the relationship between cell conditions and infestation start probabilities.

### 2.2 Infestation progression model overview

A location is "in progress" if:

- habitat is suitable (percent pine > 0 and bec zone is suitable)
- age is greater than 60 years
- beetles have been at this location at some time in the past (cumulative kill > 0)

The progress of infestations that have already started depends on:

- current infestation severity
- cumulative percentage of pine killed by beetles in all preceding years
- percentage of pine in the stand
- local beetle pressure
- long-distance beetle pressure

See Section 5 for more discussion of this aspect of the projection model, and some exploration of the relationship between cell conditions and the progress of infestations.

## 3 Calculation of beetle pressure

"Beetle pressure" is a measure of the dispersal pressure sustained in each cell. It is basically an estimate of the number of beetles that will arrive in a cell from other locations, but readers should keep in mind two distinctions between that quantity and the more conceptual "beetle pressure" measure. First, while the number of beetles that arrive in any location will be stochastic, beetle pressure is an entirely deterministic measure of the expected attack level in each cell. Second, while we hope that the relative ranking of beetle pressure values will be meaningful, we do not believe that our estimated beetle numbers will be accurate.

The "beetle pressure" calculation can be broken into several components:

- Get the number of "source" beetles. This is the expected number of beetles that will be produced at each location given the history of beetles at that location and stand characteristics (age and percent pine).
- Tabulate wind speed and direction information.
- Devise some method of distributing long-distance dispersers given wind information.
- Devise some method of distributing short-distance dispersers given the relative "attractiveness" of neighbouring cells.

### 3.1 Get number of "source" beetles

To estimate the number of beetles dispersing from each location, I rely on results from a stand level mountain pine beetle model developed by researchers at the Canadian Forest Service (Safranyik et al. 1999). Predictions from this model across a range of forest stand conditions and beetle attack levels have been tabulated for use in the regional scale MPB/SELES model. This table indicates number of beetles that will be produced and level of damage expected given a range of forest and infestation conditions. In particular, the table contains the following information:

| Category | Heading | Description |
|---|---|---|
| Predictors – forest attributes | age | age of stand |
|  | si | site index of stand |
|  | sph | density of stand |
|  | pcp | percentage of pine within stand |
| Predictors – infestation attributes | year | number of years since the infestation began |
|  | numAttackers (t-1) | number of beetles that attacked this stand last year (t-1) |
| Resultant – | numDispersers(t) | number of emerging beetles that disperse out of the source stand this year (t) |
|  | numLocal(t) | number of emerging beetles that remain in the source stand this year (t) |
|  | percentVolKill | green attack last year (t-1) or red attack this year (t) |

Table 5: Structure of the table summarizing output from the stand-level mountain pine beetle model developed by the Canadian Forest Service.

Unfortunately, we cannot use the information in CFS table directly, because we do not know the stem density of our stands, nor to we know the exact number of attacking beetles in the stand last year. Basically, we need to predict the number of beetles that will disperse from a location a given the proportion of pine killed in that year, and the age and percentage of pine in the stand.

First, I classify each *percentVolKill* number in the table into one of the five attack severity classes (Table 2). I also calculate the cumulative percentage of volume killed over all previous years of the infestation by summing *percentVolKill* over years 1 to t of the infestation, where t is the current value of *year*. I round this cumulative volume kill to the nearest 20% to get one of 6 *cumVolKill* classes.

I calculate the average number of dispersers and local beetles in each category to get a table with the following columns:

| Category | Heading | Description |
|---|---|---|
| Predictors – forest attributes | age | age of stand, classified |
|  | pcp | percentage of pine within stand, classified |
| Predictors – infestation attributes | currSeverity | Percent of pine red-attacked this year (i.e. killed last year), classified |
|  | cumVolKill | Percent of pine killed over all previous years, classified. |
| Resultant – | numDispersers | number of emerging beetles that disperse out of the source stand this year (t) |

Table 6: Structure of the table in BCMPB to provide the number of dispersers emerging from each infested cell.

### 3.2 Tabulate wind speed and direction

In the previous year of this project, we used wind information gathered from surface weather stations around BC. Surface station data is not ideal for directing long-range dispersal because it is collected at ground level. Long-range dispersal is thought to be facilitated by the convective conditions that predominate during the emergence and flight period, by lifting some beetles above the forest canopy to be passively transported by winds aloft. This year, we are grateful to build upon the synoptic climatology work of Murphy and Jackson (2004), and use more appropriate wind information in our model.

The wind information used in our long-range dispersal module now comes from the NCEP/NCAR Reanalysis Project (Kalnay et al. 1996, described in Murphy and Jackson 2004). This data set provides estimates of, among other things, the wind speed and direction at 17 pressure levels (heights) every 6 hours from 1948 to 2004.

The data is fairly coarsely resolved (every 2.5 degrees), and so cannot help us predict local movement of beetles, or the effect of topography. Ideally, it would be helpful to have more detailed wind information to guide both short and long-distance dispersal. Ongoing research at the University of Northern British Columbia hopes to address this data deficiency. In the meantime, the global reanalysis data is an improvement because it provides information about winds aloft (at 850 mb), where long-distance transport of beetles is thought to occur.

Murphy and Jackson (2004) identify heating cycles, or periods that are most likely to reflect the atmospheric conditions that exist when beetles emerge and disperse. Building on the work of Safranyik and Linton (1993) and Gray et al. (1972), a heating cycle is defined as a period of at least four consecutive days where the daily maximum temperature remained between 25 and 30 °C.

In the absence of better knowledge about the timing of beetle dispersal, last year we simply used wind data collected between the 5th and 15th of August each year. This year, we used wind data selected from the heating cycle periods identified by the synoptic climatology.

Though the wind data we use differs from last year, we treat it in the same way. Looking to summarize the average tendency of wind during dispersal periods, we calculate the proportion of times the wind blew from each direction, and the average wind speed in that direction, over the entire data period (all heating cycles between 1948 and 2004). Wind speed is in metres per second and the wind direction has a resolution of 45 compass points.

Wind speeds are, on average, lower than those used last year because the synoptic climatology focuses on fair weather periods (i.e. when synoptic pressure gradients are weak and winds are light). Our previous analysis included non-fair weather events, resulting in higher mean wind speeds.

Though the wind data we use differs from last year, we treat it in the same way. Looking to summarize the average tendency of wind during likely dispersal periods, we calculate proportion of times the wind blew in a particular direction and the average speed of wind in each direction over the entire data period (all heating cycles between 1948 and 2004). Wind speed is in metres per second. Wind speeds are on average lower than last year, in part because beetles fly in fair weather periods, and in part because I omitted no wind days from last year's analysis.

Wind direction is rounded to the nearest 45°. Angles are assigned according to geographic convention, where 0° is due north, and angles increase in a clockwise direction through east to south to west and back to north. According to meteorological convention, the "direction" of a wind is the direction from which that wind came. Thus, a north wind will blow beetles to the south from their source location. For reference, direction categories are assigned and referred to as follows:

| Direction ID | Description | Angles |
|---|---|---|
| N | Wind blows from north to south. | 337.5-22.5°, from destination to source cell. |
| NE | Wind blows from northeast to southwest. | 22.5-67.5°, from destination to source cell. |
| E | Wind blows from east to west. | 67.5-112.5°, from destination to source cell. |
| SE | Wind blows from southeast to northwest. | 112.5-157.7°, from destination to source cell. |
| S | Wind blows from south to north. | 157.7-202.5°, from destination to source cell. |
| SW | Wind blows from southwest to northeast. | 202.5-247.5°, from destination to source cell. |
| W | Wind blows from west to east. | 247.5-292.5°, from destination to source cell. |
| NW | Wind blows from northwest to southeast. | 292.5-337.5°, from destination to source cell. |

Table 7: Summary of wind direction categories.

For reference, Appendix 1a contains the broad summary of the frequency of prevailing wind directions across the province that we use. Appendix 1b contains the average wind speed in each direction.

### 3.3 Long-Distance Dispersal

I get the total number of dispersers given age, percent pine, and infestation severity in each location in each year from the information calculated in Section 3.1. These are the "source" dispersers in each location, *numSource*. I assume that some constant proportion of these dispersers will travel long distance. The actual proportion is not important, because long and short-distance beetle pressure will be independent factors in the model, and beetle pressure is a dimensionless quantity.

Wind speed and frequency vary with direction. The probability that dispersers will travel on winds coming from a particular direction is given in Appendix 1a.

I assume that long distance dispersers travel at wind speed until they land. Thus, beetle flight times will be exponentially distributed with a mean of *aveFlightTime*, where:

$$landRate = 1/aveFlightTime \qquad \text{Eq. 3}$$

and the probability of any particular flight time, $t$, is:

$$P(t) = landRate * e^{-t*landRate} \qquad \text{Eq. 4}$$

We assume beetles land at a rate of 0.001 per second, and thus remain in the air for an average of 20 minutes.

Once selected, wind speed and direction are assumed to be constant throughout the beetle flight. Thus, the distance traveled by each beetle ($x$) is equal to the flight period of that beetle multiplied by the wind speed, *currWS:*

$$x = t*currWS \qquad \text{Eq. 5}$$

The average flight distance of beetles is:

$$E(x) = aveFlightTime*currWS \qquad \text{Eq. 6}$$

Given an average wind speed of 4 m/s and an average flight time of 20 minutes, beetles will travel 5 kilometres on average.

Conceptually, the simplest thing to do would be to disperse beetles from each source over a region up to the maximum distance beetles can travel in each direction. However, at a wind speed of 4 m/s, a beetle can travel 43 kilometres in three hours. A circular region with a radius of 50 km encompasses approximately 50,000 cells in our model. In 2004, there are 441,512 infested cells in British Columbia, each producing some dispersing beetles. On the computers we have available, it takes ~30 seconds to calculate the beetle plume from one source. Multiplying by 441,512 sources, we get a calculation time of approximately 150 days for one beetle pressure map for one year.

Clearly, it is not practical to disperse beetles from each source cell independently. Instead, we employ a moving-line type algorithm, where beetles are "smeared" across the landscape in each of 8 wind directions, in much the same way that paint might smear across a canvass that is wiped with a window squeegee. Here the analogy breaks down.

because it is impossible to draw the squeegee across the canvas simultaneously in each wind direction, but that is effectively what we do.

More formally, the beetles dispersing from each source are divided into eight groups, each of which will travel in a given wind direction. The proportion of beetles traveling in each direction depends on which forest district the beetles come from (Appendix 1a). We specify a "moving-line" vector, big enough to span the beetle map (slightly longer than the longest diagonal). Beginning with the "North" wind, we start at the top of the beetle map with a line that contains no beetles. Moving from top to bottom (North to South), we pick up dispersing beetles from each source as we pass over. The line carries these beetles southward. At each step, a proportion of carried beetles are placed back on the landscape. The proportion of beetles deposited depends on the landing rate of beetles (Equation 3) and the average wind speed at that location in that direction (Appendix 1b). While beetles are carried forward by the line, they also diffuse laterally; at each step, 40% of beetles are moved to the adjacent cell in each direction (20% in each direction), and 40% are moved 2 cells away in each direction. 20% of beetles remain in place. When we arrive at the bottom edge of the map, we repeat the spreading process for each of the 7 other wind directions.

Figure 3 shows the results of this smearing process for 2002. First, we see the price that is paid for the greater computational efficiency of our moving line algorithm in the star patterns that form around our beetle sources. This computational artifact could be countered by increasing the number of "swipes" we take with our moving-line, but this takes time. The map shown seems to us an acceptable compromise.

Figure 3 shows at least some amount beetle pressure everywhere in the province. The lowest value represents an expectation that approximately 1/10,000,000,000 of one beetle will at this location per year. Clearly, such a small likelihood of dispersal probably has no real effect on beetle dynamics in these areas. In the current version of the model, we have chosen to consider long-distance beetle pressures of less than –0.5 as negligible. Below this level, we do not see any significant effect of beetle pressure on infestation start probability. Beetle pressure values above 4.5 are considered uniformly "high", and we resolve beetle pressure classes to a width of 1 unit per class. Figure 4 shows the classified beetle pressure map for 2002. Depending on the severity of source infestations, and local wind speed, long-distance beetle pressure can be significant up to ~100 kilometres away from the source.

Acute observers may note that our beetles travel less far than last year (Figure 3), but that we consider a broader range of pressure values significant (Figure 4). Beetles travel less far because we kept the same landing rate while decreasing average wind speed. Our beetle landing rate is arbitrary, so we could have decreased the landing rate to compensate for lower wind speeds. However, we find that the more condensed pressure pattern better predicts observed beetle spread, so choose to keep the new version as it is. This result emphasizes that long-distance beetle pressure in our model is not mechanistic. We are not interested in modeling beetle dispersal per se, but in characterizing the spatial autocorrelation of beetles in whatever way works. We also note that a far more thorough analysis of spatial structure in this data would be interesting and useful.

### 3.4 Short-distance dispersal

Dispersers that do not travel long-distance distribute themselves among cells within one kilometre of their host cell. In general, the probability of beetles dispersing to a location depends on the quality of habitat at that location, the distance from the source location, the direction of the prevailing wind, and the number of beetles already at that location. As much as possible, I have tried to follow the approach to short-distance dispersal used in SELES/MPB. However, that model takes an iterative approach to short-distance dispersal, where later dispersing beetles make decisions based on the movement of earlier dispersing pioneer beetles. Here, we aspire to a more efficient one-step dispersal model, and so must take a somewhat different approach.

First, in SELES/MPB, the probability that a beetle will move to a particular location is:

$$0.00000001 + distanceFactor * hostFactor * windFactor * hostFactor * pheromoneFactor \quad \text{Eq.7}$$

Where:

$$distanceFactor= 1/d^2 \qquad \text{Eq. 8}$$

*d* is the distance from the beetle source in cell widths. I adopt this portion of the model as it is.

The *hostFactor* in SELES/MPB is:

$$hostFactor=(1-cumKill/100)*SusceptibilityIndex/100 \qquad \text{Eq. 9}$$

I cannot adopt this approach directly because we are missing some of the information necessary to calculate the susceptibility index. Using the information we do have, I calculate the *hostFactor* as:

$$hostFactor= (1-cumKill/100)* (age>60)*pcp/100 \qquad \text{Eq. 10}$$

Again using the information available, I take the *windFactor* directly from Appendix 1a. *windFactor* varies with forest district and the direction to the source location. See Section 3.2 for more details.

The effect of the *pheromoneFactor* is to attract beetles to areas with some other beetles, and repel them from areas that are too crowded. The problem is that I wish to move all beetles simultaneously. Thus, I move beetles on the basis of wind, distance, and host quality alone, and omit the pheromone factor from this model.

## 4 Infestation start model

Factors in the infestation start model are not independent from one another. Single factor views are convenient and easy to understand, but can be misleading because they obscure interactions between variables. With this in mind, we move away this year from single factor views to a more complex multi-factor view (Appendix 2).

Because local and long-distance pressure are related to one another, not all combinations of these two factors are observed (Figures a2_1 – a2_5). Basically, if long-distance pressure is less than 2, local pressure will be low. We are not concerned that the model is unspecified when long-distance pressure is low and local pressure is high, because we do not expect that this condition will ever arise. At the margins, there are a few cases where long-distance pressure is 2 and local pressure is 3 (Figures a2_2, and a2_5), or where long-distance pressure is 3 and local pressure is 5 (Figures a2_2 to a2_5). Clearly these beetle pressure conditions may occur, if rarely. Perhaps, in future, different kind of stand may also be subject to low beetle pressure than we have observed thus far. In this case, the model will not start an infestation, though in the real world that might be warranted. Thus, infestations may start a little less often at the margin than our model predicts.

Overall, the probability of infestation starting increases with both local and long-distance beetle pressure (Figures a2_1 – a2_5). This effect is consistent over all percent pine categories. Over age categories, there is some variability, but the trend is consistent. If we integrate over all percent pine and age categories for a global view (Figure 5), the trends are also apparent, though it looks here like increasing local pressure decreases start probability when long-distance pressure is 3. The problem here is that there are very few cases where local pressure = 5 and long-distance pressure =3, so the model is largely unspecified in that case (Figures a2_1 to a2_5).

The effect of age on infestation starting varies with percent pine and beetle pressure, and is thus more difficult to discern. When percent pine is low, age seems to have little effect (Figure a2_1). When percent pine is higher, it seems that the effect of age varies with long-distance pressure. When percent pine and long-distance pressure are moderate (3), the probability of infestations arising seems to decrease with stand age (Figures a2_2 and a2_3). As percent pine gets even higher (and pressure remains moderate), start probability is highest in intermediate aged stands (Figure a2_5). Where pressure is higher (4 and 5), start probability is highest at intermediate age across a wider array of percent pine classes. Integrating over other factors, the probability of starting is lower at higher ages (Figure 6).

It would be worth doing some statistical analysis to better understand how the effect of age varies with percent pine and beetle pressure. More particularly, which of the trends noted above are significant, and worthy of interpretation? I will not speculate further here, but simply note that, on average, the model predicts better when age is included as a factor than when it is not.

The effect of increasing percent pine is clearer. That is, infestations are more likely to start in areas with more pine, but are more likely to be severe in areas with less pine (Figures a2_2 to a2_5, Figure 7). Readers from last year may recall that the effect of percent pine was less intuitive before we added the 2004 data to the model. Then, it appeared that stands with 100% pine were less likely to be infested than stands with 75-99% pine. That effect was statistically significant even taking into account the interaction with other factors. The odds of a cell being infested when percent pine is 75-99% were 1.114 (1.098, 1.132) times higher than the odds of a cell being infested when percent pine is 100%, directly adjusted for age, long-distance pressure and local pressure. 'Odds' is defined as the probability that the cell is infested over the probability that the cell isn't infested. The fact that the confidence interval does not include 1 indicates that this was significant result. The Logistic regression model was fit using the LOGISTIC procedure in SAS.

When we add the 2003 and 2004 data, the situation changes. Now, the odds of a cell being infested when percent pine is 75-99% is 0.727 (0.719, 0.734) times the odds of a cell being infested when percent pine is 100%. This is more as we expected. We suspect the counterintuitive result from early years of the outbreak can be explained by observing that much of the pure pine in British Columbia is concentrated in the Chilcotin plateau, which was not significantly infested until 2003. The difference between 100% and 75-99% pine stands appeared significant because our beetle pressure factors do not account for all the spatial structure in the observed data.

## 5 Infestation Progression Model

Last year, we felt that the beetle time-series was too short to drive a reasonable infestation progress sub-model. Instead, we used output from the landscape level mountain pine beetle simulation model muMPB to drive infestation progress. The problems with the observed data were real, but the muMPB approach turned out to be imperfect also. The problem is that muMPB predicts beetles will kill less pine than the aerial overview survey shows. We do not know whether muMPB predicts badly because the aerial overview survey over-estimates kill, because our process for scaling up within-stand dynamics to large areas is flawed, or because beetles in the CFS stand model are not as aggressive as beetles in real life. We suspect a combination of all three reasons. Regardless, an muMPB driven progress model does not project a believable trajectory (Figure 8).

Now, we have one more year of beetle data (2004), making a total of 6. We see infestations declining near the center of the outbreak, giving a more complete view of the progress of outbreaks, and a much higher number of observations overall (46% increase). Is there now enough data to drive a progress model? Actually, it turns out that most of those new observations end up in already specified parts of the model, but there are 100 gaps filled in by the new data. Though this is a relatively small proportion of the total model (3%), they define what happens when cumulative kill is high and outbreaks are declining, and are thus relatively important. Given that the muMPB projection is not believable, we accept the remaining unspecified cases, and use the data-driven approach.

|  | number of observations | % cases unspecified |
|---|---|---|
| Progress from 1999 to 2004 | 1,301,405 | 69 |
| Progress from 1999 to 2003 | 892,583 | 72 |
| Progress from muMPB | 1,978,013 | 29 |

Table 8: Characteristics of a progress model driven with data from 1999 to 2004, from 1999 to 2003, and from the muMPB landscape model.

Using data to drive the progress model helps make our projection look more believable, but does not help us understand or resolve the discrepancy between muMPB projections and the survey data. For that, we need to know what proportion of pine beetles actually kill, on the ground in real forest stands. We submit that this is one of the most conspicuous and problematic gaps in our understanding of mountain pine beetles, and a major obstacle to understanding the future impacts of this outbreak.

Finally, the major component missing from our model at this point is climate. We know that this factor is important for beetles, and hope in future to integrate the results of a mountain pine beetle initiative project on climate into this model. It may be impossible to incorporate climate into our data driven progress model, so we may have to revisit the muMPB option at that point.

Factors in the infestation progress model not independent of one another. Single factor views are convenient and easy to understand, but can be misleading because they obscure interactions between variables. With this in mind, we take a multi-factor view of the infestation progress model (Appendix 3).

First, we note that many combinations of the factors in the progress model were not observed over the period of record (1999-2004). This is a problem only if the unobserved conditions will arise in future. With this in mind, we examine the gaps in the progress model more closely.

Over the period from 1999 to 2004, most (72%) of infestations occur where both local and long-distance beetle pressure are high (4). Under these beetle pressure conditions, the model is generally well specified (Figure a3_1). The only combination not often observed is high cumulative kill and endemic current infestation. This says that, in the data, infestations do not tend to decline to endemic after they have been severe – they either remain more severe, or go out completely.

What will the model do if it encounters a location that is endemically infested, with high cumulative kill? The general instruction when the model encounters an unspecified probability is to reduce infestation severity by one class (to no beetles, in this case), then to reduce cumulative kill by one class, and repeat this sequence until it encounters a specified probability. In this particular case, the model will refer to the probability distribution for areas with no beetles (Column 1 in Figure a3_1). To us, that seems reasonable, and unlikely to affect model results.

Fewer infestations (2%) are observed where long-distance pressure is very high (4), and local pressure is intermediate (3), in part because this condition occurs less often across the landscape. While 2% is low, it is not negligible, including almost 25,000 cases. Examining Figure a3_2, we observe a trend that continues through the remainder of the progress model (Figure a3_3 – a3_11). That is, more severe infestations are rarely observed in areas with lower beetle pressure. First, note that infestations do not exert beetle pressure on themselves. So the observation is that severely infested areas tend to be within 1km of other infestations (within which region local pressure is exerted). To us, this seems fairly reasonable, and unlikely to change radically as beetles move into other areas of the province. For argument's sake, though, consider what the model will do if it encounters an isolated infestation – first, reduce infestation severity, then cumulative kill, and so on until a specified probability is reached. By this process, the model tends to diffuse or snuff out isolated severe infestation that it does not know what to do with. If anything, the result will be to slow beetles in isolated areas.

More infestations (9%) are observed where long-distance pressure is very high (4) and local pressure is low (2) than when local pressure is intermediate (3). This is because local pressure is low across most of the landscape, and intermediate only in small parts of it. More generally, fewer infestations occur as beetle pressure declines. Since local and long-distance beetle pressure are correlated, it is almost never true that local beetle pressure is high or intermediate while long-distance pressure is low (<3), so the transition probabilities under these conditions are almost completely unspecified, and we omit them from this appendix.

| | local pressure = 2 | local pressure = 3 | local pressure = 4 |
|---|---|---|---|
| long-distance pressure = 2 | 2.76 | 0.00 | 0.00 |
| long-distance pressure = 2.5 | 1.77 | 0.04 | 0.04 |
| long-distance pressure = 3 | 3.03 | 0.20 | 0.59 |
| long-distance pressure = 3.5 | 4.11 | 0.58 | 3.71 |
| long-distance pressure = 4 | 8.73 | 1.91 | 72.52 |

Table 9: Proportion of infestations that occur in various beetle pressure conditions.

So what is the effect of beetle pressure on the progress of infestations? In a single factor view (Figure 9) we see the danger of not considering the interactions between factors. At face value, it looks like increasing local beetle pressure decreases the probability an outbreak will continue. This is counter to expectations, and can be understood by noting that local beetle pressure is correlated with cumulative kill by beetles. Infestations in areas with very high beetle pressure are often very advanced, and thus more likely to decline. Accounting for these other factors, outbreaks are more likely to continue and more likely to be severe when beetle pressure is high (Figures a3_1 to a3_5).

Because such a high proportion of infestations are observed in high beetle pressure areas, that is a good place to look at the effect of percent pine, cumulative kill and infestation severity on infestation progress (Figure a3_1). First, percent pine (Figure 10). Infestations are more likely to become severe when percent pine is low (comparing rows). Recall that severity refers to the percentage of pine that is infested, not the size of the beetle population. When percent pine is low, it takes fewer beetles to make an infestation severe. Thus, it is not surprising that infestations become severe more often in these areas. It is interesting that, once started, percent pine seems to have little effect on the chance that an infestation will continue.

What is the effect of cumulative kill on infestation progress? As we might expect or hope, the probability of an infestation continuing, or becoming more severe, tends to increase as cumulative kill increases from low to intermediate, and the infestation becomes established (Figure 11). As cumulative kill increases further, the probability of the infestation continuing declines again. If nothing else, an infestation must go out when cumulative kill reaches 100%.

Once an infestation is severe, it is more likely to stay severe (comparing columns in Figure a3_1, and Figure 12). Again, this is as we expect.

Age seems to have little effect on infestation progress (Figure 13). The infestation progress sub-model is already somewhat over-specified, including so many levels of so many factors that there are not enough cases of each type upon which to draw convincing conclusions. To avoid further over-specification, we omit age from the progress sub-model.

## 6 Projection model testing

Last year, we parameterized the model with data from 1999 to 2002, keeping 2003 data in reserve for testing. This year, we drive the progress sub-model with observed data. We are barely comfortable with how well specified the progress sub-model is when 2004 data is included. If we leave the 2004 data out, the model will not know what to do with outbreaks that are declining. Predicting 2004 without knowing what to do with old outbreaks does not seem like a useful test of the model.

Even without an independent test set, it is still worth considering how well or badly the model predicts the observed data. We look at how well the model predicts each year from the previous (2000 from 1999, and so on), and also at how errors compound over time by projecting to 2004 starting in 1999.

First, we take a global view, comparing the pine volume killed by beetles in the observed data to our various projections (Figure 14). When we project just one year forward (1999 to 2000, 2000 to 2001 and so on), we over-predict in the first two years, and under-predict in the last two. This means that the outbreak is escalating more quickly than the factors in our model account for, a conclusion confirmed when we project 2004 from 1999 (Figure 14). Why this might be, we do not know. We expect it will be less a problem in future because both our projection and the observed data show the rate of increase in this outbreak is starting to decline (Figure 14). Note that all numbers reported here are for the timber harvesting land-base only.

How well does the model predict the spatial distribution of beetles? First, beetles are more scattered in the projection than in the observed data (Figures 15 to 17). After 5 years, basically all the spatial structure is gone from the outbreak (Figure 18). This means we have not captured all the spatial structure in the data. A look at volume killed by management unit also shows that beetles are more clumped in reality than in our projection (Figure 19). The model tends to under-predict kill in heavily infested areas and over-predict in less infested areas. A more thorough analysis of spatial autocorrelation in the beetle data could improve this aspect of the model.

What about exceptions to the general trend? Where does the model do particularly badly, and why? Lakes and Fort Saint James are notable because they are heavily infested, but the model under-predicts (Figure 19). There are no lightly infested (<2% of susceptible thlb volume killed in 2004) when the model under-predicts in 2004, but areas where it over-predicts more than usual include Mackenzie, Golden, and Morice. What is special about these areas? Topography, climate, extra management activity, and unique beetle history are all possibly important factors. We speculate no further here.

In the model, we have made some distinction between infestations that are already in progress, infestations that start where there is significant local beetle pressure, infestations that start where there is only long-distance beetle pressure, and infestations that start in areas where there is no significant beetle pressure. To understand which components of the model might be performing worse than others, we look at how the model performs in each of these four situations. Figure 20 shows the number of infested cells observed and predicted in each of these categories.

In the infestation in progress sub-model, we under-predict severe infestations, and over-predict the other severity classes (Figure 20). Infestations continue to escalate faster than we expect. We over-predict starts in almost all categories, especially where beetle pressure is negligible (starts are emergent). This tells us that new infestations started less often in the same conditions in 2004 than in previous years. It is worth recalling here that we significantly under-predicted starts in 2003 (last year), mostly because we failed to predict infestation spread into the Chilcotin. It looks in retrospect like 2003 was a particularly expansive year for beetles, a pattern not repeated in 2004 or in years previous.

## 7 Projecting forward

Our base run begins in 2005 and goes for 20 years to 2024, and includes no management interventions. Figure 21 shows how the proportion of susceptible volume killed increases over that period. In 2004, beetles have killed 14% of susceptible pine in the province. By 2009, beetles kill 54% of susceptible pine, and by 2024 95% of susceptible pine has been killed by beetles.

## 8 Sensitivity analyses

I have investigated 8 areas of uncertainty in the mountain pine beetle model:

- Wind: Does the wind information we have included improve our ability to predict infestation spread?

- Local dispersal: Does a simpler local dispersal model improve our projection?
- Site index: Does including site index as a factor improve our model projection?
- Endemic area: Our data processing method may lead to an overestimate of the area affected by endemic beetle infestations. How does reducing (or increasing) the endemic area affect the progress of the infestation?
- Beetle allocation method: In the base run, I allocate beetles in each 1 kilometre area among the suitable habitat cells in that area. How does changing the beetle allocation rule affect simulation results?
- Uncertainty about forest age:
- Uncertainty about percent pine on the landscape:
- Uncertainty about the proportion of kill in low infestation areas:

## 8.1 Wind

The average wind speed in our model is 3.6 m/s. To check whether the wind data we have included has a significant effect on the spread of infestations, I assumed that wind travels at a constant speed of 3.6 m/s equally often in all directions across the province. Removing wind from the model in this way makes effectively no difference in the progress of the infestation, suggesting that wind is unimportant to beetles, that our treatment of wind information is inadequate, or that the wind data we have is uninformative (Figure 22).

## 8.2 Simple Short Distance Dispersal

I simplify the short-distance dispersal model by allocating dispersing beetles equally among neighboring cells, removing the effect of distance, wind, and habitat quality. Over the whole province, simplifying the short distance dispersal model does not make any significant difference in the progress of the infestation or the effect of management (Figure 22).

## 8.3 Site Index

First, a preliminary analysis shows that the probability of an infestations beginning does vary with somewhat with site index. According to the infestation progression sub-model, site index has a less clear effect on the progress of infestations once they have arisen (Figures 23 and 24). Including site index as a factor decreases the volume killed by beetles (Figure 22). However, adding a new factor to the model increases the problem of over-specification. Some of the effect of site index is because site index predicts infestation severity, and but some of it is due to new unspecified gaps in the model. When we additionally take into account that site index estimates in the forest cover database are not particularly accurate, we conclude that site index should not be added to the provincial projection model. Adding a climate factor to the model will account for similar effects (cold places should be bad for beetles) in a more direct way.

### 8.4 Reducing the endemically infested area

Removing endemic infestations makes basically no difference (Figure 22). In fact, removing ¾ of these low level infestations actually speeds up the outbreak slightly. This is because removing endemic infestations frees up the landscape for more severe infestations to start in high-pressure areas. Apparently, the start model is more sensitive to changing beetle pressure than the progress model.

### 8.5 Beetle allocation method

In the data processing for this model, I begin with the number of beetles in each 1200 by 1200 metre area. Each of these large cells encompass 9 400 metre by 400 metre cells. In the base case, I allocate the beetles in each large cell among those of the 9 smaller cells that are suitable for beetles. For example, in an area with 9000 beetles and 2 out of 9 suitable habitat cells, each suitable cell would get 4500 beetles. In this alternative scenario, I allocate beetle among all cells, so the ones that fall in unsuitable habitat are erased from the landscape. In this case, 1000 of our 9000 beetles are allocated to each of the 2 suitable cells, and the remaining 7000 beetles are erased. Overall, between 25 and 45% of beetles are erased from the landscape each year between 1999 and 2004 in this scenario (compared to 9-20% in the base case – Figure 25).

Removing 20% of beetles from the landscape reduces the amount killed (Figure 22). Over the 20 years, beetles kill 88% of susceptible pine in this more optimistic scenario (compared to 94% in the base case). If there were fewer beetles between 1999 and 2004, and the outbreak increased more slowly over that period, the prediction is that beetles will kill less, less quickly in the future.

### 8.6 Uncertainty about forest age

Uncertainty about the age of forests increases with increasing forest age. We examined the sensitivity of the beetle model to the possibility that forests tend to be younger than the forest cover data suggests (Case 1 – younger forests). To do this, we reduced forest age by 20 years in 55% of areas where the recorded age is > 240 years. 45% of areas aged 221-240 years were reduced by 20 years, and so on according to the scheme in Table 10. In the second case, we increase forest age by 20 years according to the last column in Table 10 (20 years added to 50% of areas aged 221-240, and so on).

| Class id | age class | 1 - younger forest | 2 - older forest |
|---|---|---|---|
| 0 | 0 | 100 % in class 0 | 100 % in class 0 |
| 1 | 1-20 | 100 % in class 0 | 100 % in class 0 |
| 2 | 21-40 | 100 % in class 0 | 100 % in class 0 |
| 3 | 41-60 | 5% to class 2 | 5% to class 4 |
| 4 | 61-80 | 10% to class 3 | 10% to class 5 |
| 5 | 81-100 | 15% to class 4 | 15% to class 6 |
| 6 | 101-120 | 20% to class 5 | 20% to class 7 |
| 7 | 121-140 | 25% to class 6 | 25% to class 8 |
| 8 | 141-160 | 30% to class 7 | 30% to class 9 |
| 9 | 161-180 | 35% to class 8 | 35% to class 10 |
| 10 | 181-200 | 40% to class 9 | 40% to class 11 |
| 11 | 201-220 | 45% to class 10 | 45% to class 12 |
| 12 | 221-240 | 50% to class 11 | 50% to class 13 |
| 13 | >240 | 55% to class 12 | 100% in class 13 |

Table 10: Scheme for analysis of sensitivity to forest age.

Changing forest age by the amount described has basically no effect on the beetle projection model (Figure 26).

### 8.7 Uncertainty about percent pine

Uncertainty about the percentage of pine in forests decreases with increasing percent pine. I first examined the sensitivity of the beetle model to the possibility that there is less pine on the landscape than the forest cover data suggests (Case 1 – less pine). To do this, I reduced percent pine by 25% in 10% of areas with 75-99% pine. I reduced the percentage of pine in 20% of cases with 50-74% pine and so on (Table 11). In the second case, I increase the percent pine by 25% according to the last column in Table 11.

| **class id** | **pcp class** | **1 - less pine** | **2 - more pine** |
|---|---|---|---|
| 0 | 0 | 100% in class 0 | 50% to class 0 |
| 1 | 1-24 | 40% to class 0 | 40% to class 2 |
| 2 | 25-49 | 30% to class 1 | 30% to class 3 |
| 3 | 50-74 | 20% to class 2 | 20% to class 4 |
| 4 | 75-99 | 10% to class 3 | 10% to class 5 |
| 5 | 100 | 100% in class 5 | 100% in class 5 |

Table 11: Scheme for analysis of sensitivity to percent pine.

Increasing percent pine by the amount described decreases the amount killed by beetles in the near term, while decreasing percent pine has no significant (Figure 26). Why should increasing pine decrease beetle kill? Proximally, because we find in the observed data that 100% pine stands are less likely to start severely infested than 75-99% stands, and once infested, they are less likely to stay or become severely infested (Figures 7 and 10). Why is that? Recall that severity is a percentage of pine killed. The same amount of beetles will be more severe in an area with less pine. Next, note that I altered only the percent pine attribute of cells, not the actual volume of pine across the landscape. In reality, higher percent pine would also mean higher pine volume, and more volume lost. So actually, increasing the percent of pine will probably increase the total volume killed by beetles. But the percentage of pine killed might decrease slightly.

### 8.8 Redefining low severity infestations

In the base case, we assume that in areas marked "low" severity in the overview data percent kill ranges between 1 and 10% of susceptible pine, with an average of 5%.

|  | Lower | "Mid" | Upper |
|---|---|---|---|
| Severe | 0.2 | 0.3 | 1 |
| Moderate | 0.1 | 0.15 | 0.199999 |
| Low | 0.01 | 0.05 | 0.099999 |

| | | | |
|---|---|---|---|
| Endemic | 0.000001 | 0.005 | 0.009999 |
| None | 0 | 0 | 0 |

Table 12: Severity definitions in the base case.

In this alternative scenario (*Low25)*, I assume that the overview data overestimates kill in low severity areas, and that "low" severity areas actually contain 1 to 5% kill, with an average of 2.5%.

| | Lower | "Mid" | Upper |
|---|---|---|---|
| Severe | 0.2 | 0.3 | 1 |
| Moderate | 0.05 | 0.15 | 0.199999 |
| Low | 0.01 | 0.025 | 0.049999 |
| Endemic | 0.000001 | 0.005 | 0.009999 |
| None | 0 | 0 | 0 |

Table 13: Severity definitions in the *Low25* scenario.

Removing endemic infestations has very little effect on the progress of the infestation, but redefining "low" severity changes the outbreak quite a lot. I presume this is because the infestation progress model predicts a very different future for a stand with 2% kill than one with 5% kill.

### 8.9 Summary of sensitivity results

The model is basically insensitive to: removing wind; simplifying short-distance dispersal; reducing the number of endemic infestations in the starting condition; and uncertainty about forest age. The model is somewhat sensitive to: including site index; and uncertainty in percent pine. The model is sensitive to: altering the beetle allocation method, and redefining what low severity means.

Although the model is acutely sensitive to our interpretation of low severity, we do not propose to change this definition in future versions of the model. We have no data to suggest what a better choice would be. We leave off this topic with a note that any data on about the "meaning" of the aerial overview survey data is of interest, and that the reliability of our projections is constrained by the reliability of the input survey data.

Although the model is slightly sensitive to site index, we also do not propose to include this factor in future versions of the model. The site index data is suspect, and we imagine that a weather/climate factor may provide some of the same information.

## 9 References

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Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, and D. Joseph. 1996. The NCEP/NCAR 40-year reanalysis project. Bulletin of the American Meteorological Society 77:437-471.

Murphy, B. D., and P. L. Jackson. 2004. A synoptic climatology for the emergence and flight of the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) in the central-interior of British Columbia. *in* The 26th Agricultural and Forest Meteorology/13th Air Pollution/5th Urban

Environment/16th Biometeorology and Aerobiology, Vancouver, British Columbia.

Safranyik, L., H. Barclay, A. Thomson, and W. G. Riel. 1999. A population dynamics model for the mountain pine beetle, Dendroctonus ponderosae Hopk. (Coleoptera : Scolytidae). Pacific Forestry Centre, c1999. vi, 35 p. : ill., Victoria, B.C.

Safranyik, L., and D. A. Linton. 1993. Relationships between catches in flight and emergence traps of the mountain pine beetle, Dendroctonus ponderosae Hopk. Journal of the Entomological Society of British Columbia **90**:53-61.

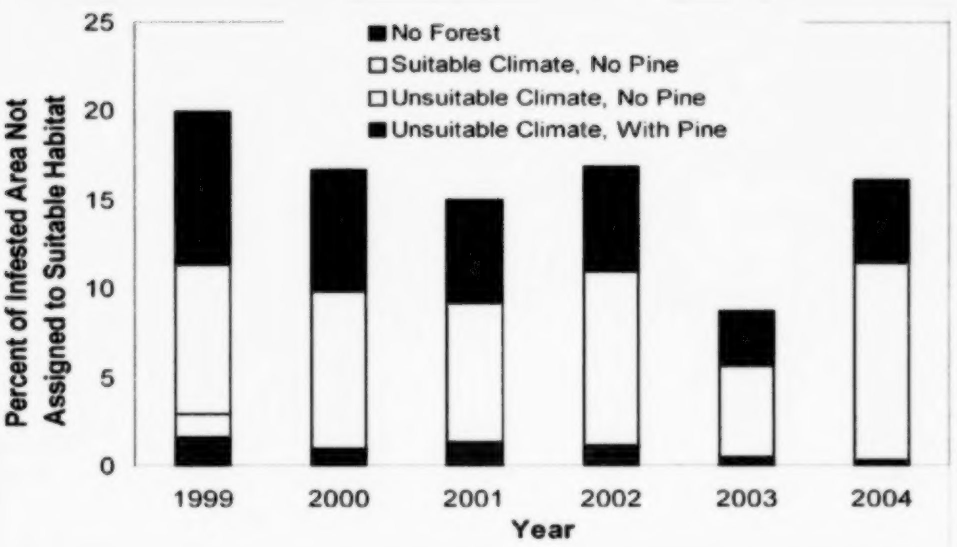


Figure 1: Reasons for loss during beetle allocation. The aerial overview survey data reports more beetles in some areas than there is forest to accommodate those beetles. Where possible, we allocate beetles to adjacent suitable habitat, on the assumption that the spatial location of the infested polygon might not be exact. However, we do not find places to put all of the extra beetles. Here, we show the proportion of beetles lost, and the type of area in which they were lost.

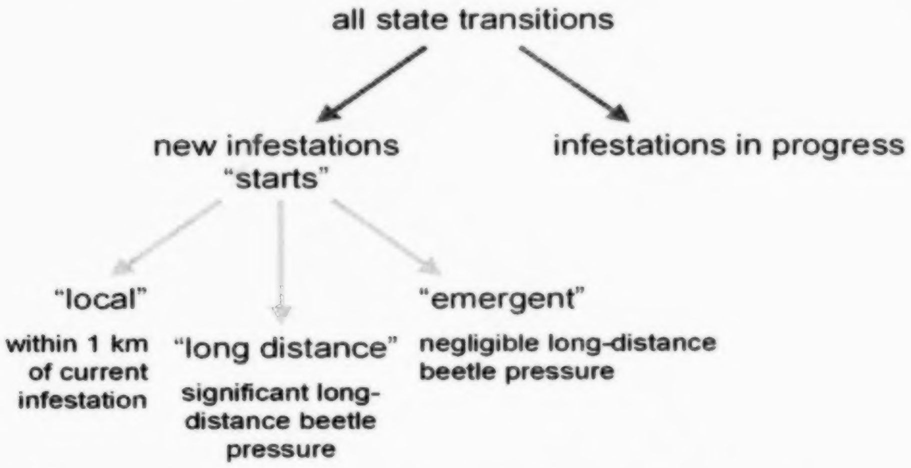

all state transitions
new infestations
"starts"
infestations in progress
"local"
within 1 km of current infestation
"long distance"
significant long-distance beetle pressure
"emergent"
negligible long-distance beetle pressure

Figure 2: Four sets of conditions in the mountain pine beetle transition model.

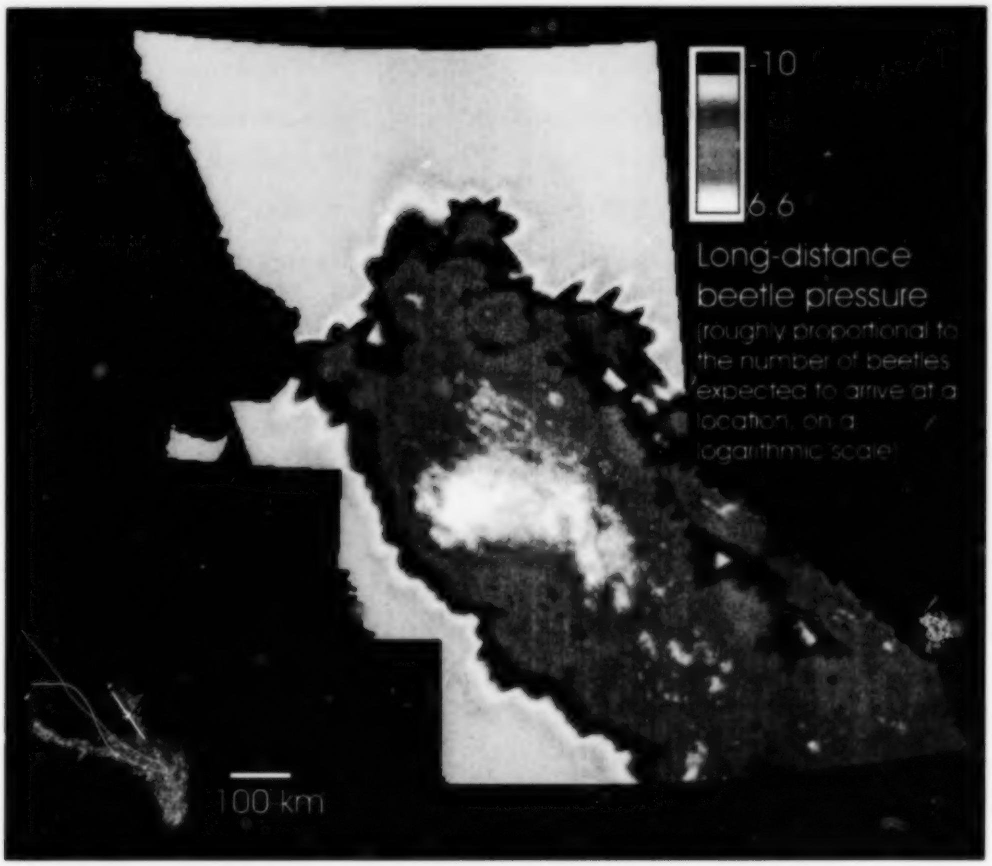

-10
6.6
Long-distance beetle pressure
(roughly proportional to the number of beetles expected to arrive at a location, on a logarithmic scale)
100 km

Figure 3: Long-distance beetle pressure in 2002, calculated using a moving-line algorithm. Beetle pressure is shown on a logarithmic scale. Pressure is a measure of the relative number of dispersing beetles expected to arrive at a location, but is a dimensionless quantity. To illustrate, we could reasonably expect that 10 times more beetles might arrive in an area with a beetle pressure of 2 than a beetle pressure of 1. We could not reasonably claim that 200 hundred beetles will arrive at locations with a beetle pressure value of 2.

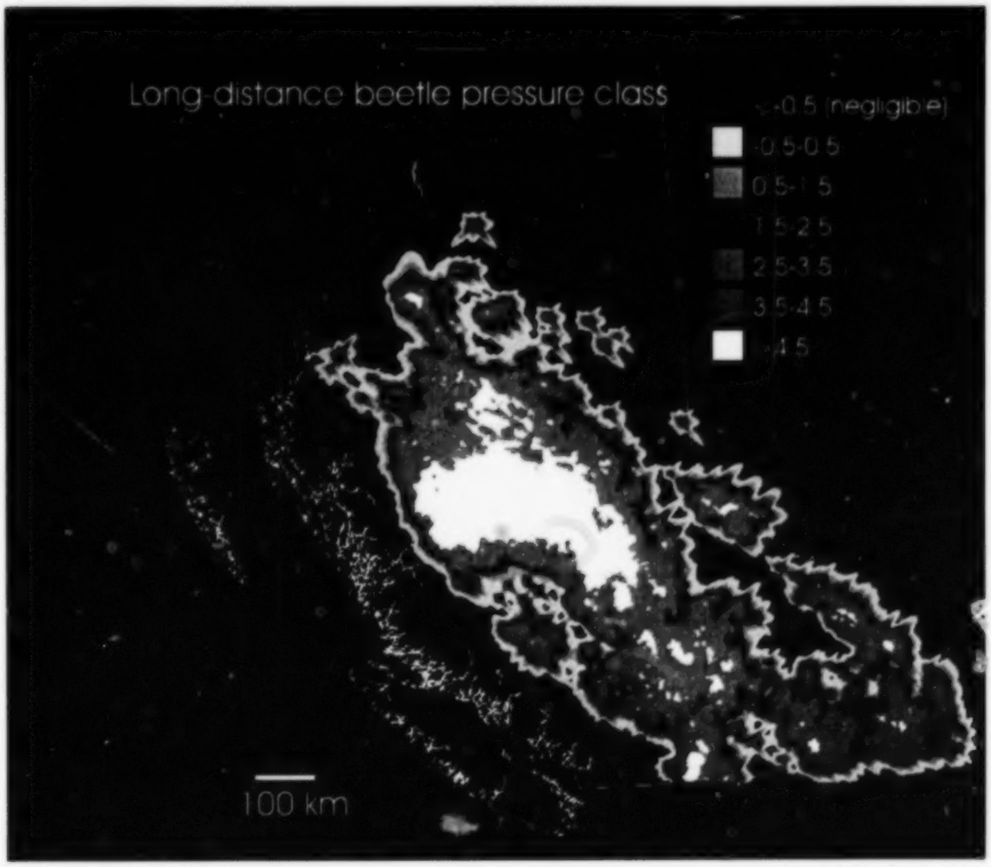

Long-distance beetle pressure class
<-0.5 (negligible)
-0.5-0.5
0.5-1.5
1.5-2.5
2.5-3.5
3.5-4.5
>4.5
100 km

Figure 4: Long-distance beetle pressure classified into classes of 1 order of magnitude. Pressure values of less than –0.5 are considered negligible, having no significant effect on mountain pine beetle dynamics in these areas.

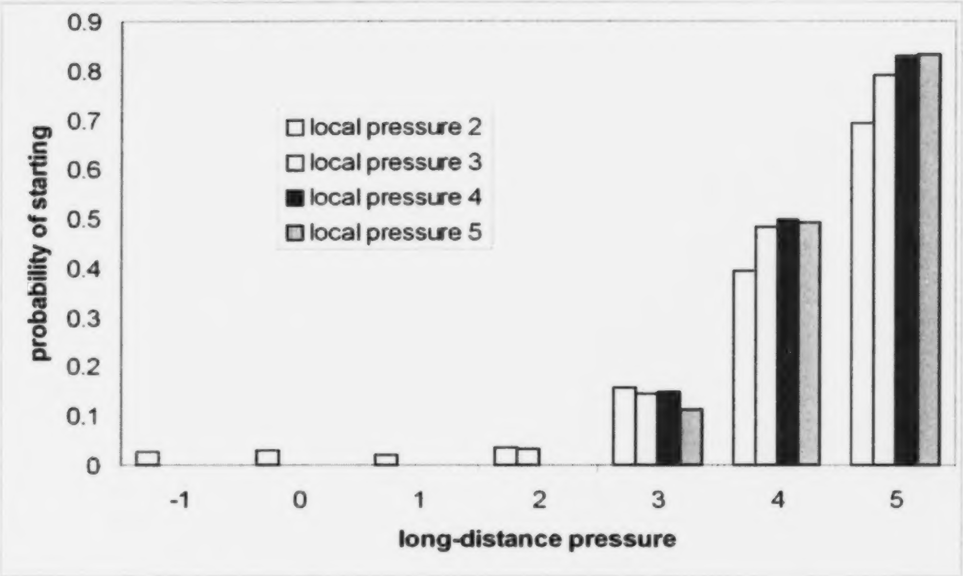


Figure 5: The effect of beetle pressure on the probability an infestation will start in an area that has never before been infested.

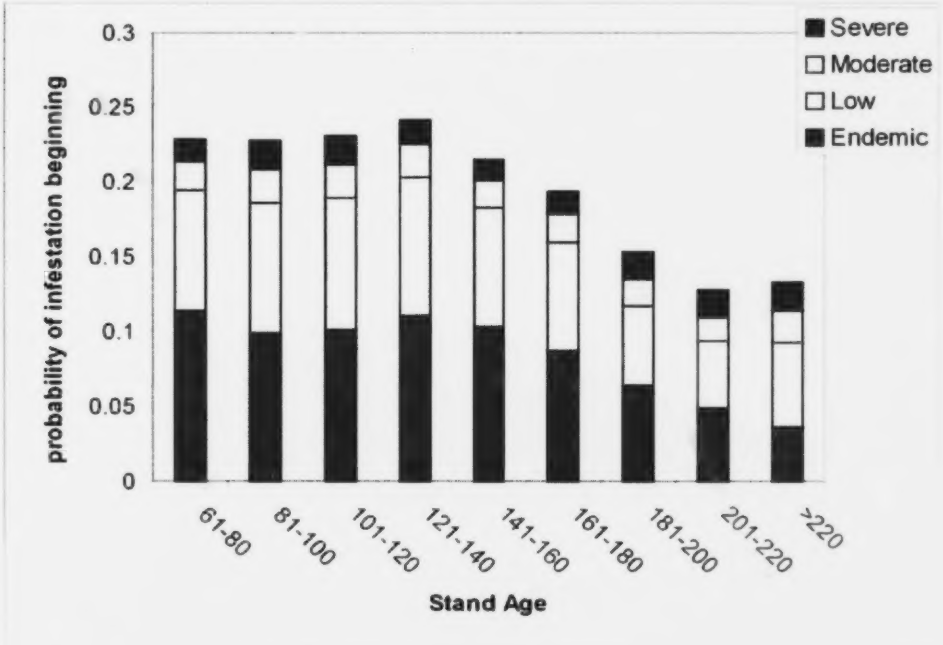


Figure 6: The effect of stand age on the probability an infestation will start in an area that has never before been infested.

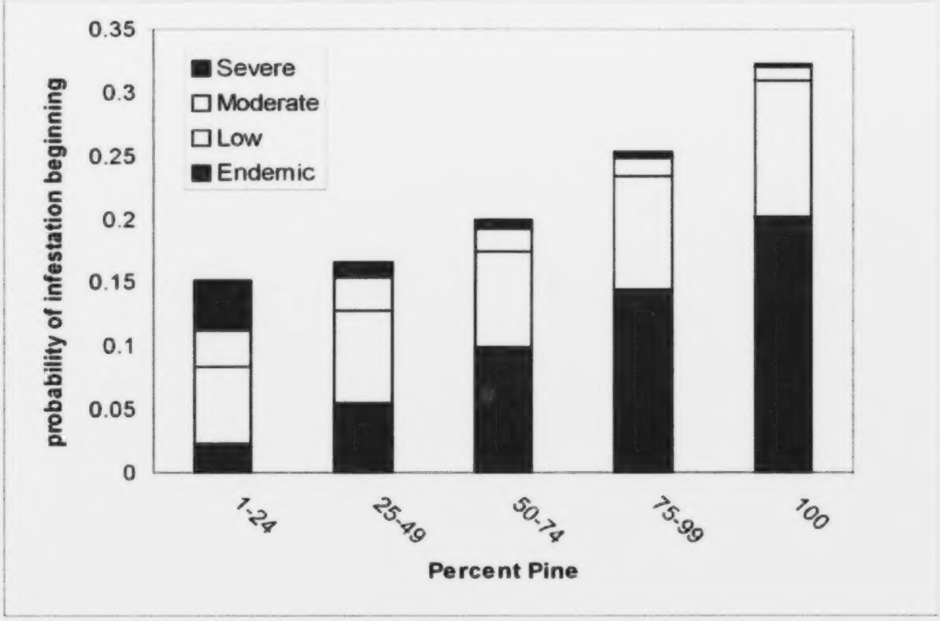


Figure 7: The effect of percent pine on the probability an infestation will start in an area that has never before been infested.

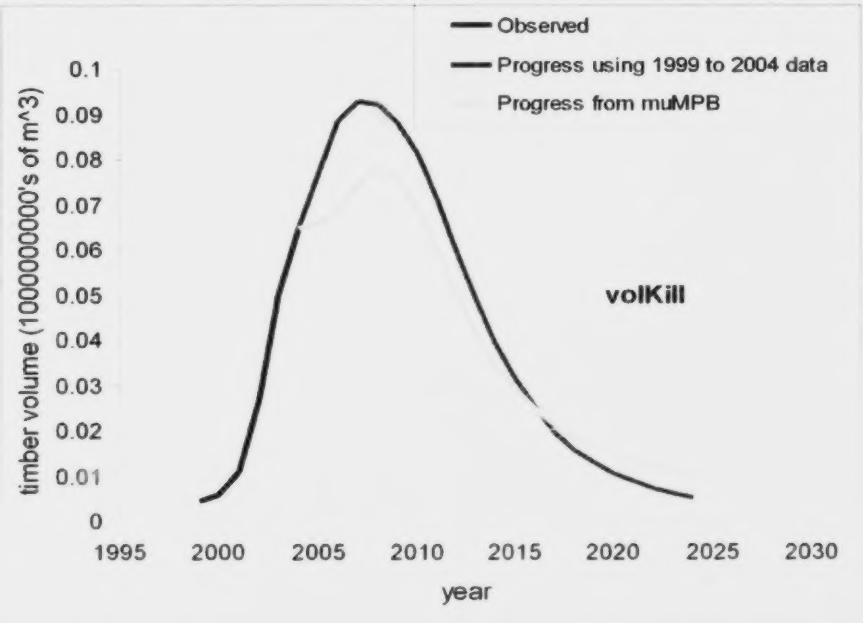


Figure 8: Progress of an outbreak driven with an muMPB-based progress sub-model, compared to a data driven sub-model.

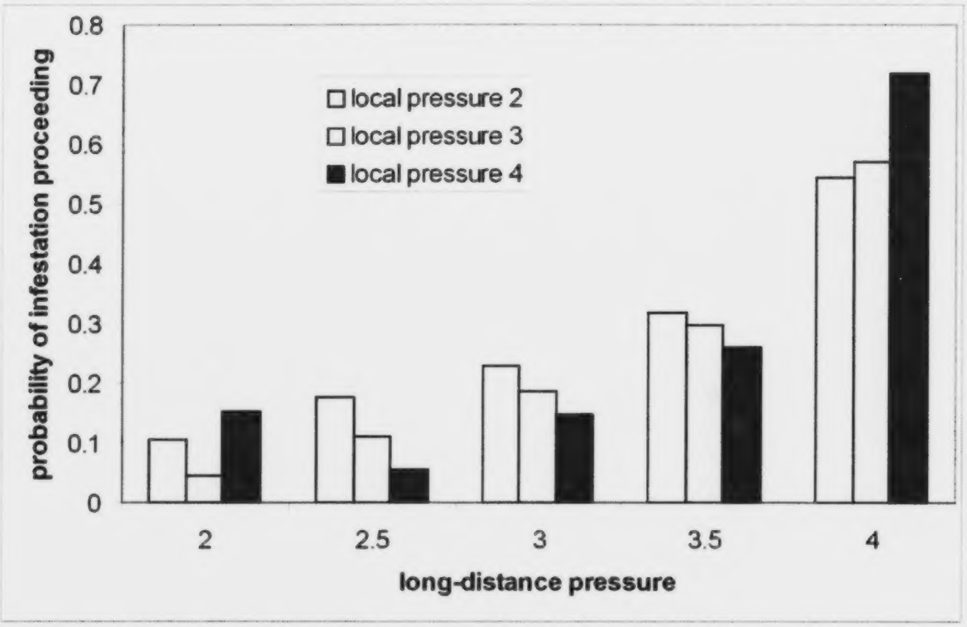


Figure 9: The effect of beetle pressure on the progress of infestations.

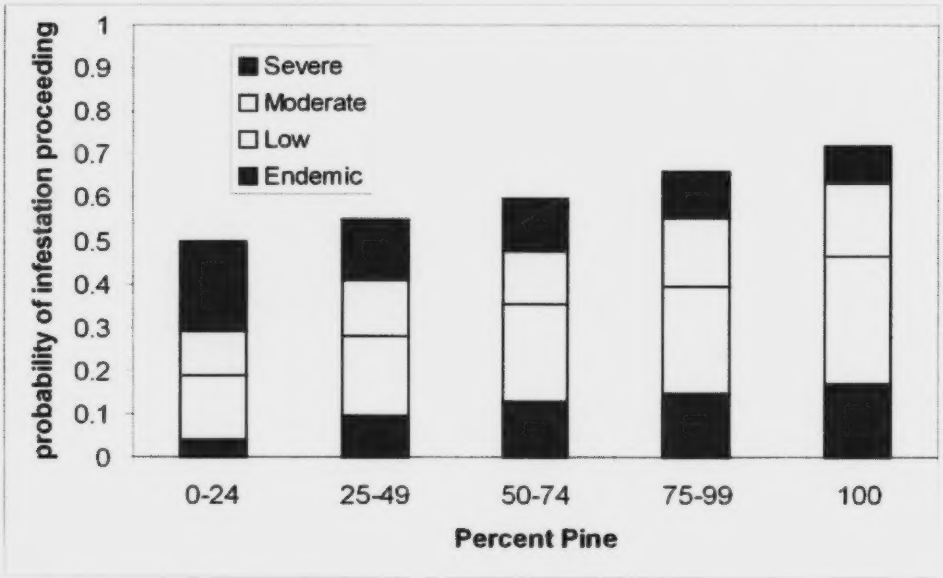


Figure 10: The effect of percent pine on the progress of infestations.

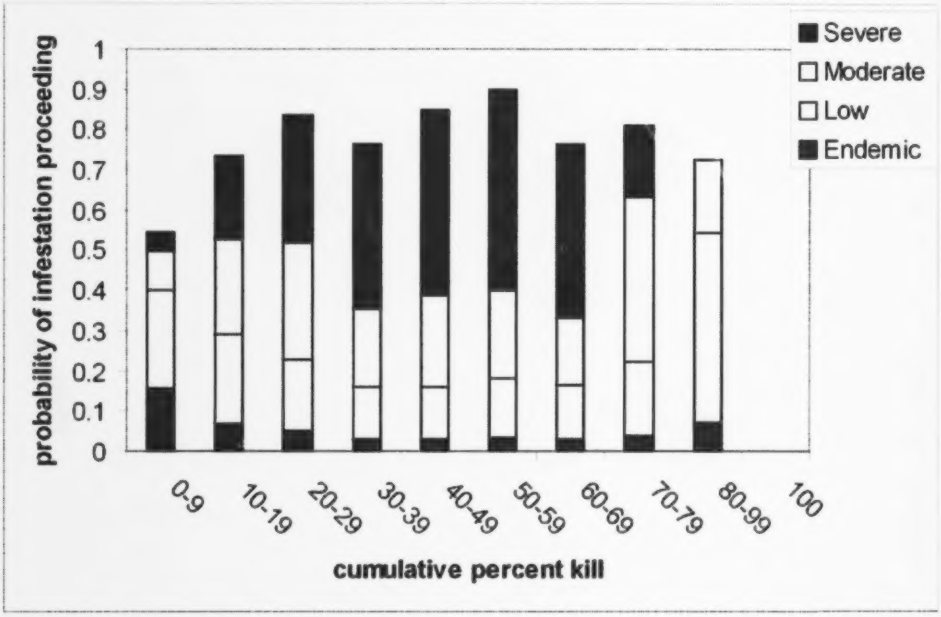


Figure 11: The effect of cumulative kill on the progress of infestations, modified to stop infestations from continuing after cumulative kill reaches 100%. Cumulative kill values are approximate, estimated from mid-point values for each severity class, rather than exact knowledge.

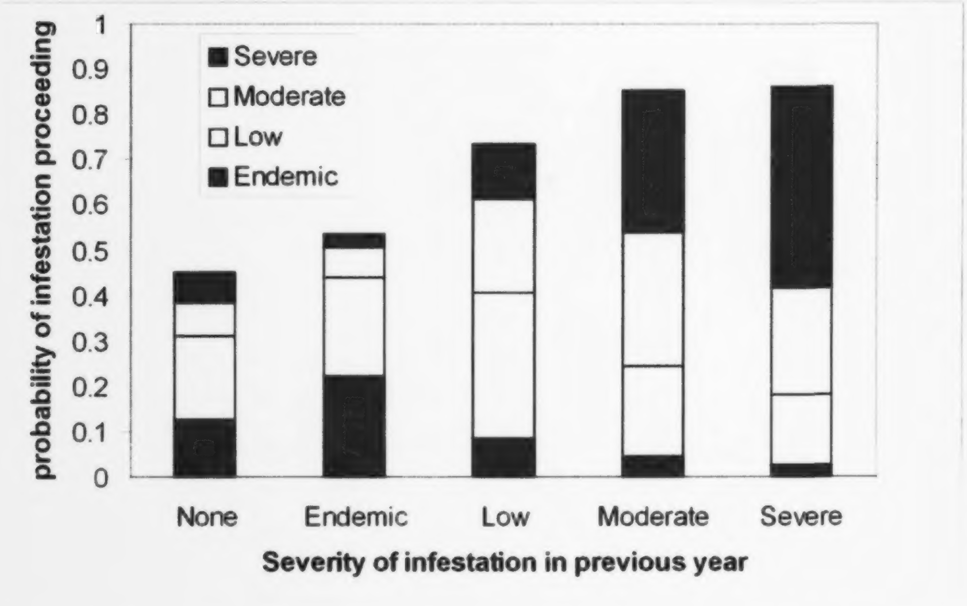


Figure 12: The effect of current infestation severity on the progress of infestations.

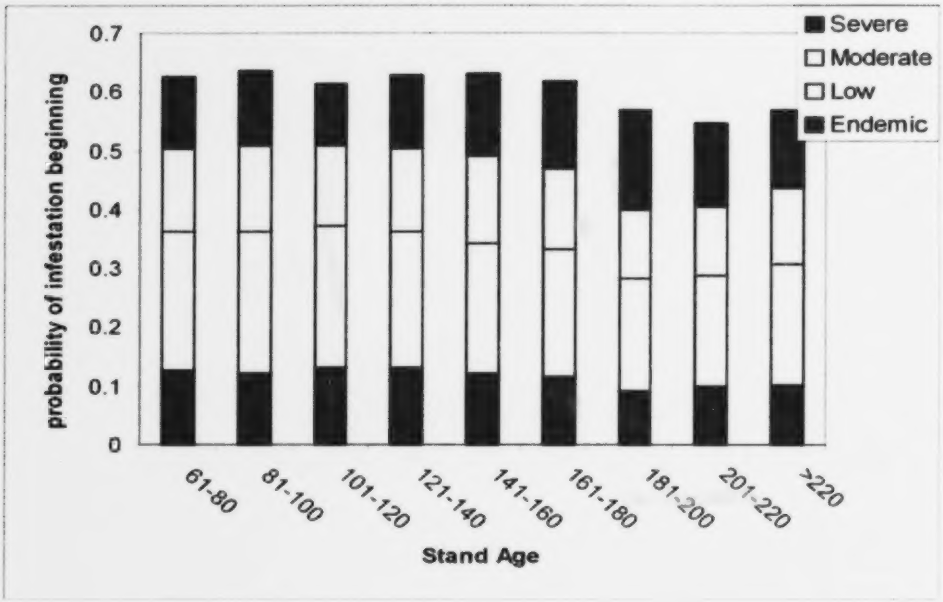


Figure 13: The effect of stand age on the progress of infestations.

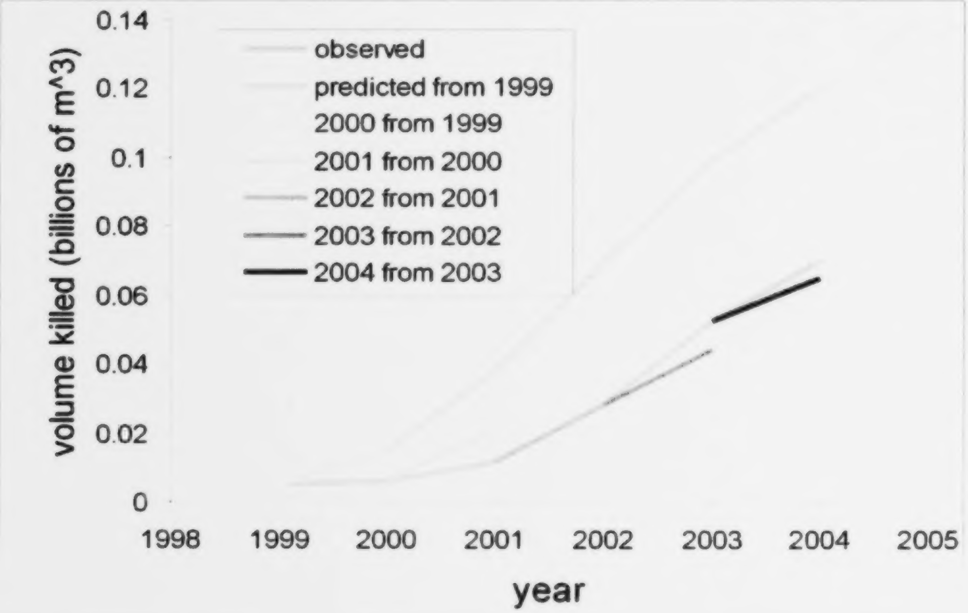


Figure 14: Annual pine volume killed by beetles across the timber harvesting land-base between 1999 and 2004. Predictions are from a projection model parameterized with 1999 to 2004 data.

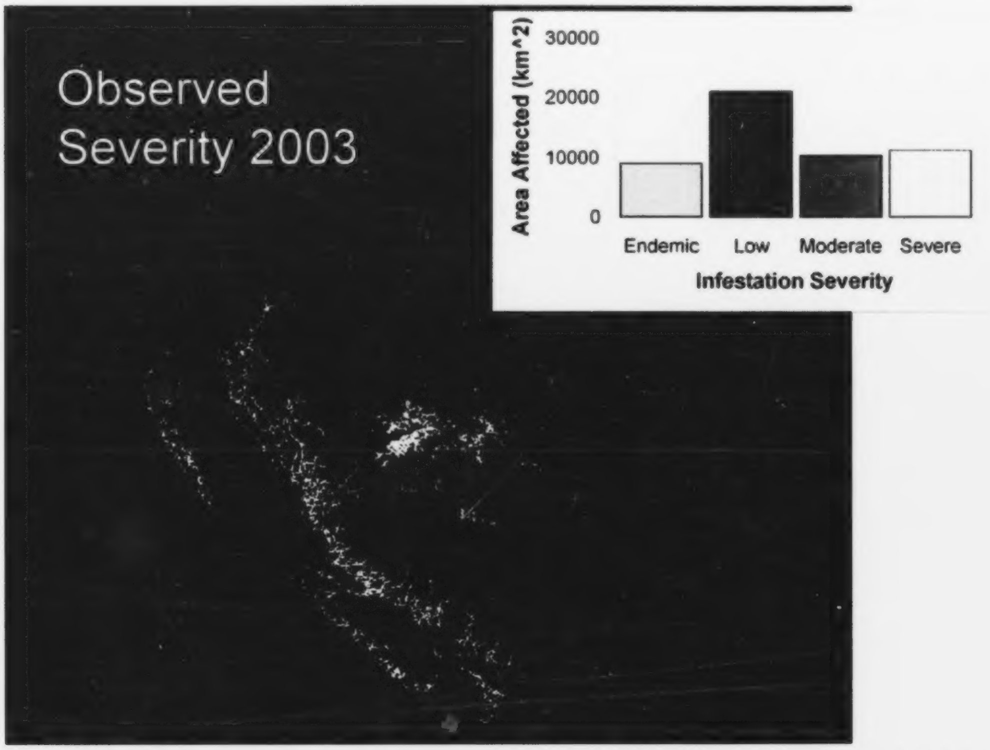

Observed
Severity 2003
Area Affected (km^2)
30000
20000
10000
0
Endemic
Low
Moderate
Severe
Infestation Severity

Figure 15: Observed mountain pine beetle severity in 2003 according to processed aerial overview survey data.

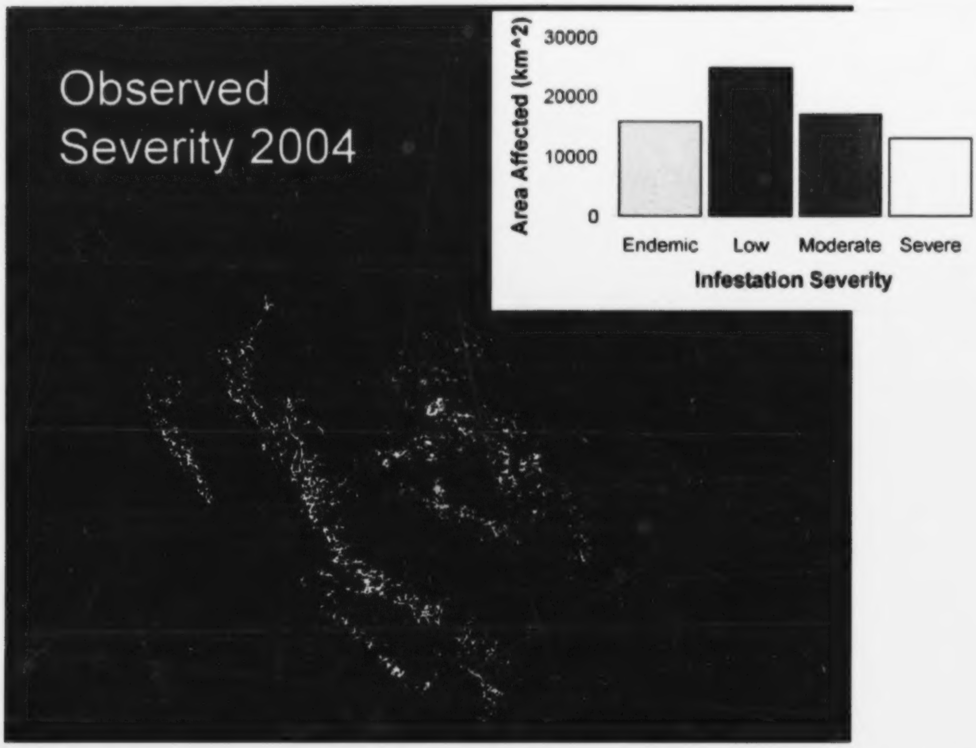

Observed Severity 2004
Area Affected (km^2)
30000
20000
10000
0
Endemic
Low
Moderate
Severe
Infestation Severity

Figure 16: Observed mountain pine beetle severity in 2004, according to processed aerial overview survey data.

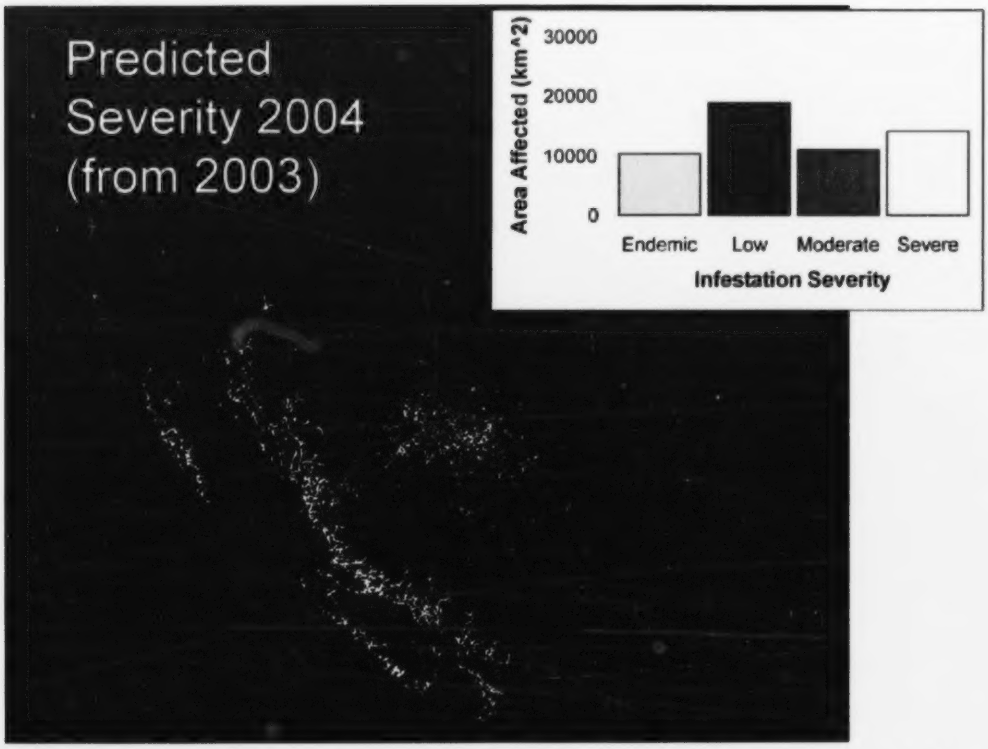

Predicted
Severity 2004
(from 2003)
Area Affected (km^2)
30000
20000
10000
0
Endemic
Low
Moderate
Severe
Infestation Severity

Figure 17: Mountain pine beetle severity in 2004, predicted by our projection model from observed mountain pine beetle severity in the preceding year (2003).

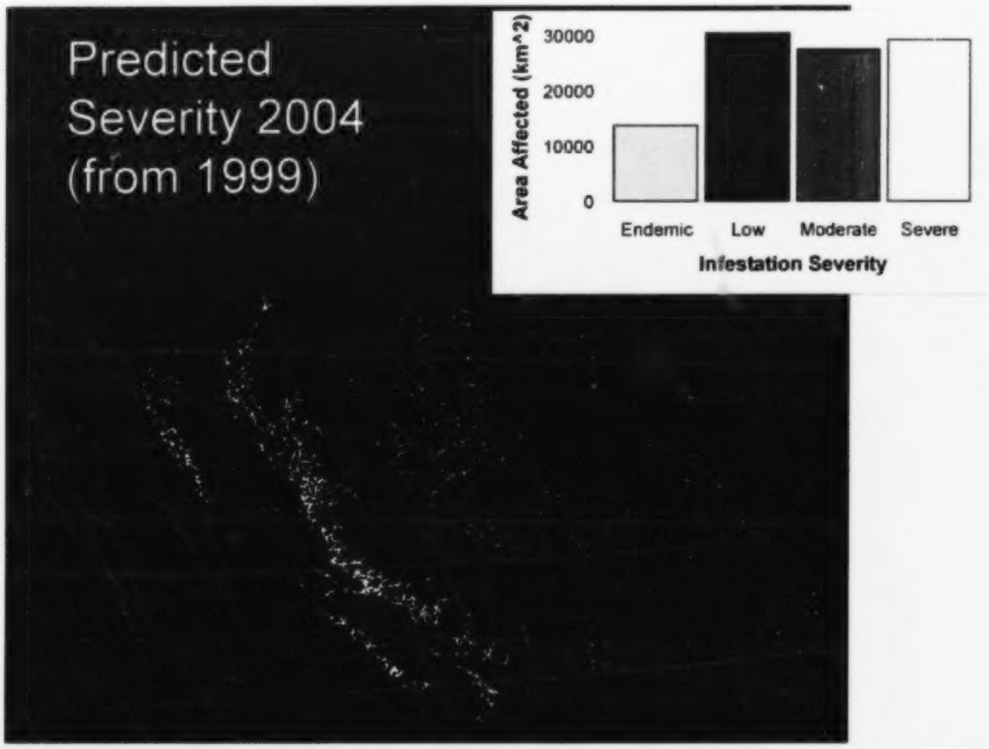

Predicted
Severity 2004
(from 1999)
Area Affected (km^2)
30000
20000
10000
0
Endemic
Low
Moderate
Severe
Infestation Severity

Figure 18: Mountain pine beetle severity in 2004, predicted by our projection model from observed mountain pine beetle severity in 1999.

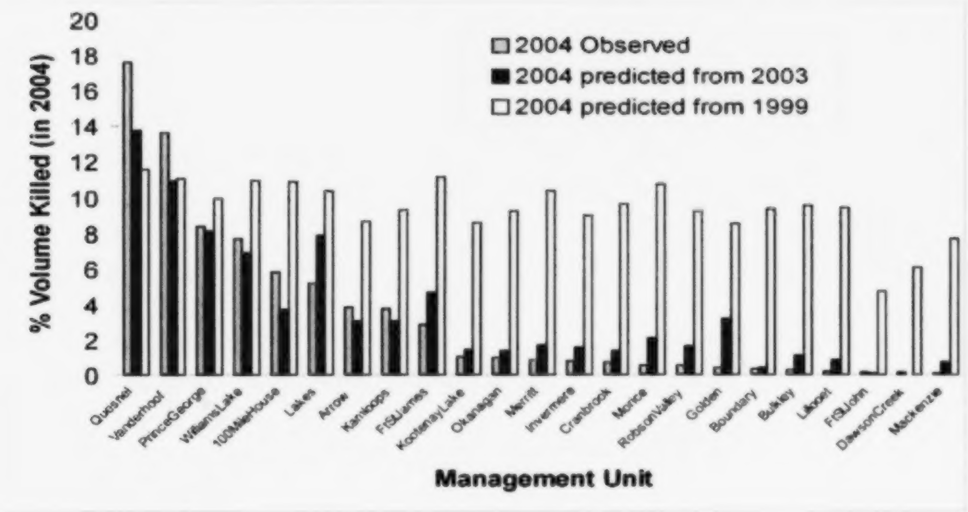


Figure 19: Variation in the performance of the projection model between mountain pine beetle management units. Over one year, the model tends to under-predict volume killed in heavily infested areas, and over-predict kill in less infested units. Over 5 years (from 1999), the spatial structure in the outbreak is essentially lost.

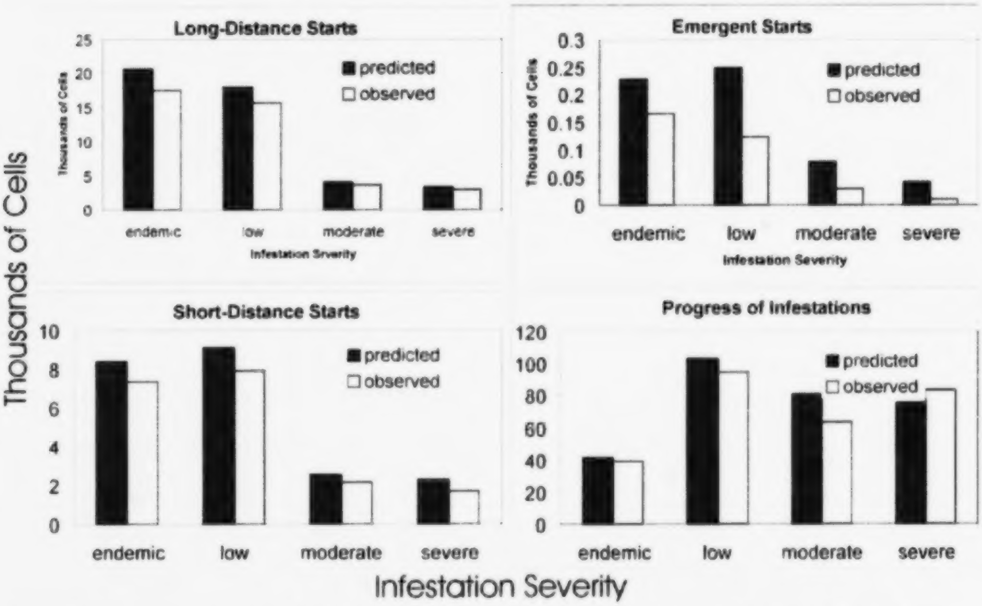


Figure 20: Performance of the projection model in each of four model sub-sections. The model over-predicts everything except the number of severe infestations in progress. Despite over-predicting in most categories, the model under-predicts volume killed (Figure 14).

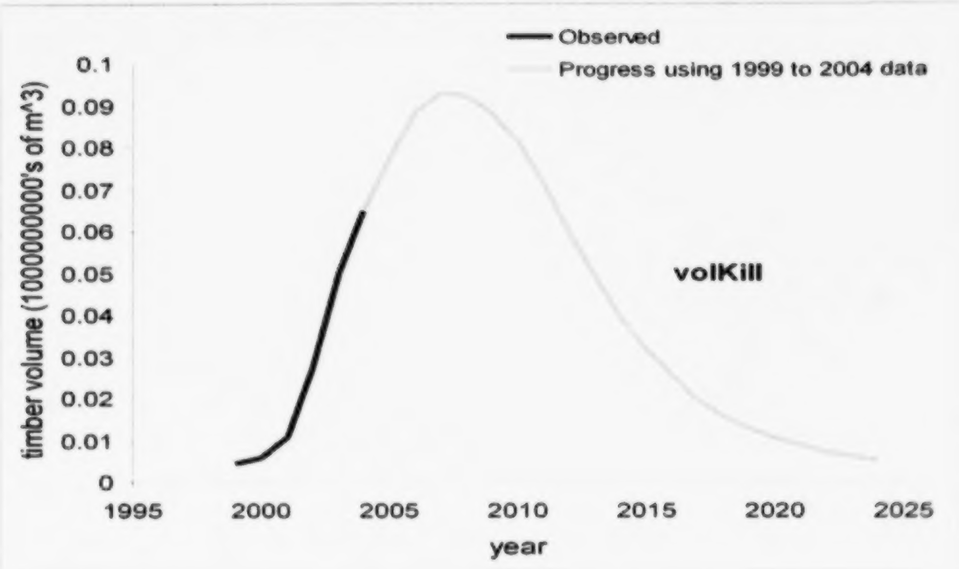


Figure 21: Long-term behaviour of the mountain pine beetle model in the absence of any management intervention. Values before 2005 are from observed data, while values after are the result of one 20-year run of the projection model starting in 2004.

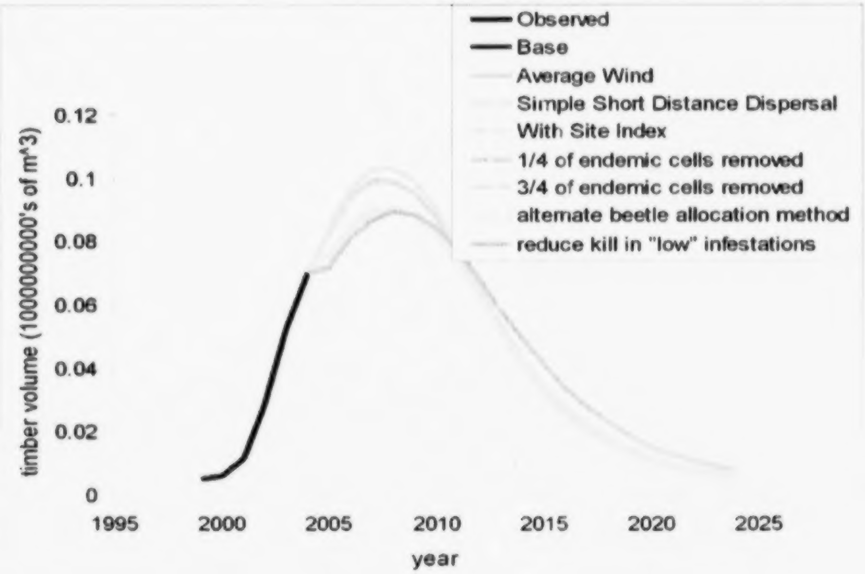


Figure 22: Effect of a range of factors on the volume killed by beetles.

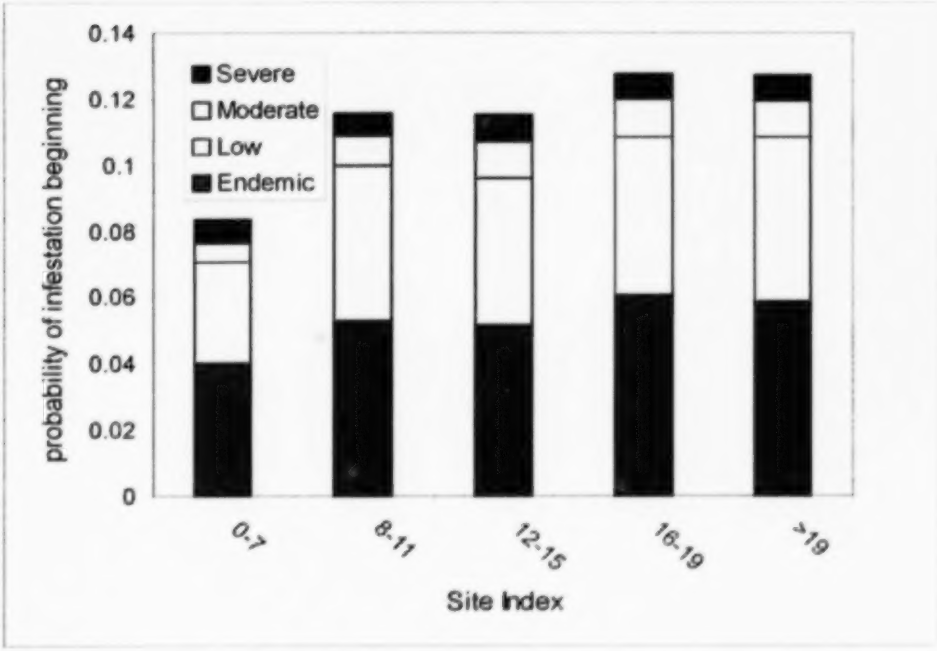


Figure 23: Effect of site index on the probability of infestations starting.

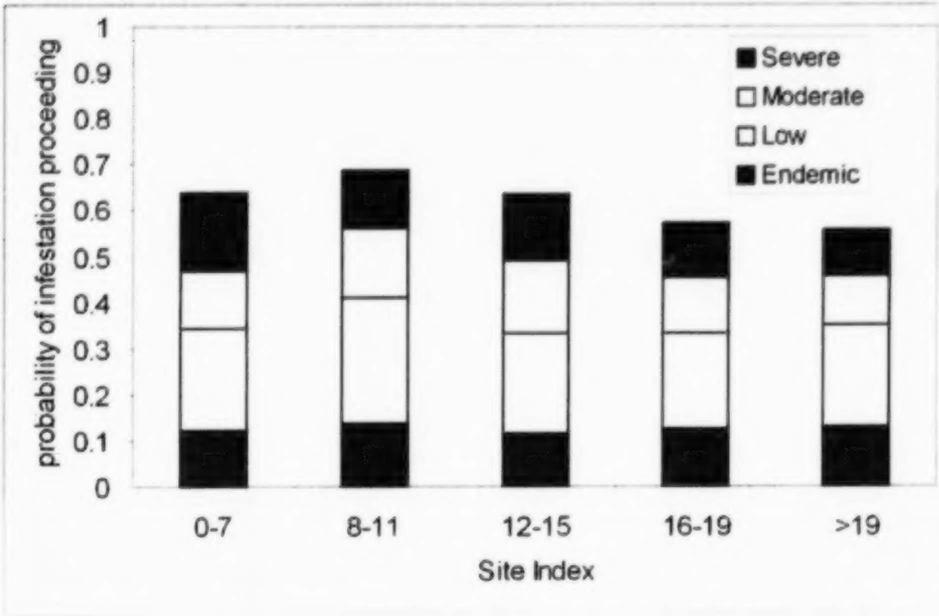


Figure 24: Effect of site index on the probability of infestations proceeding.

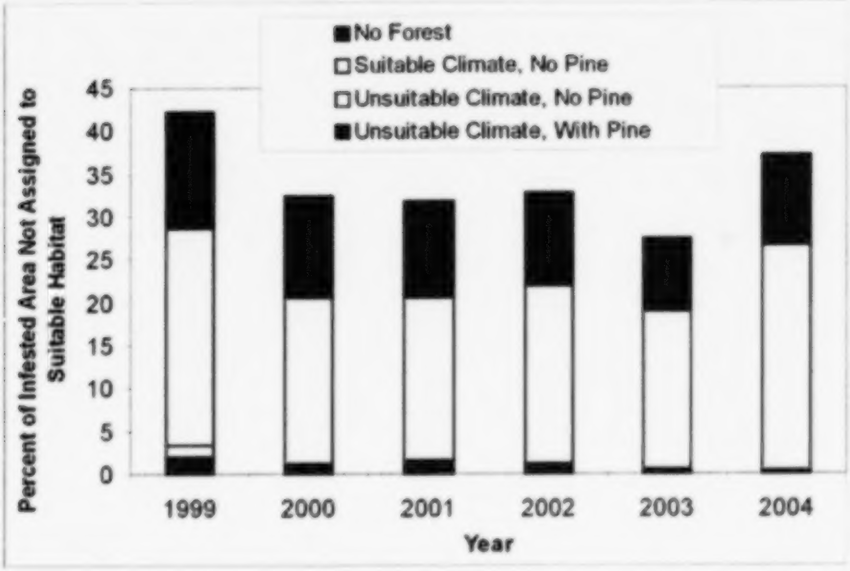


Figure 25: Percent of beetles lost in our alternate beetle allocation scenario. The aerial overview survey data reports more beetles in some areas than there is forest to accommodate those beetles. In the base case, we allocate beetles to adjacent suitable habitat, on the assumption that the spatial location of the infested polygon might not be exact. Here, we allocate beetles equally among suitable and unsuitable areas.

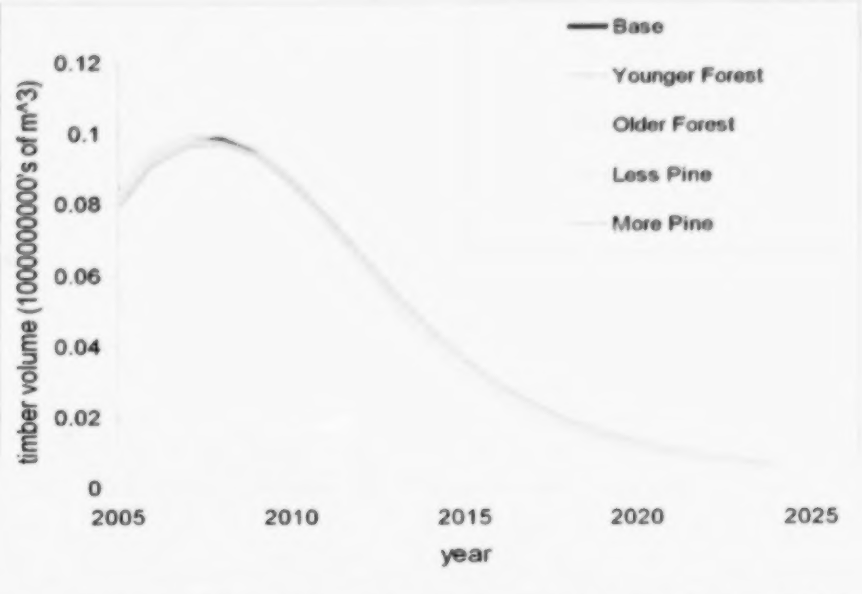


Figure 26: Effect of changing forest age and percent pine on the volume killed by beetles.

**Appendix 1 a: Relative frequency of prevailing wind directions across the province:**

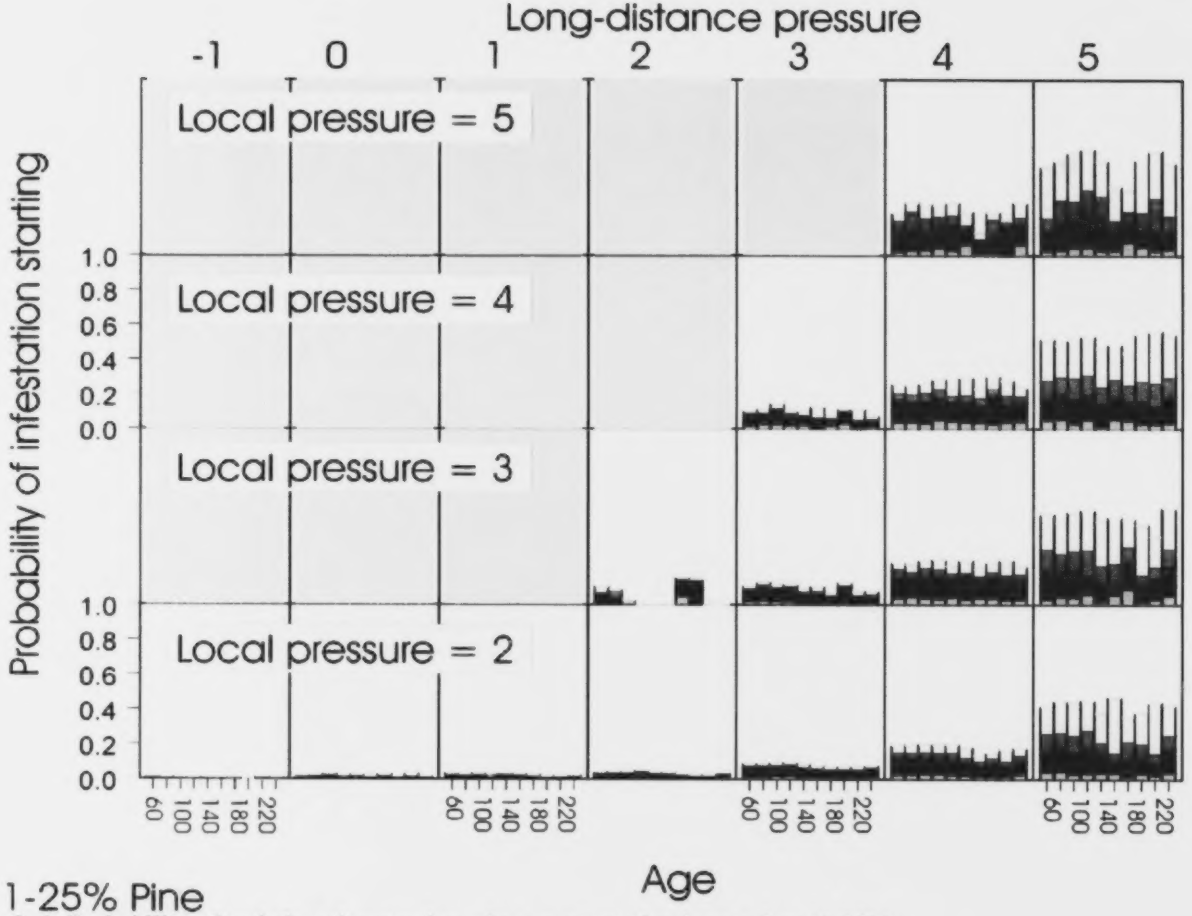
| Latitude | Longitude | N | NE | E | SE | S | SW | W | NW |
|---|---|---|---|---|---|---|---|---|---|
| 47.5 N | 122.5 W | 15 | 13 | 15 | 12 | 15 | 9 | 6 | 14 |
| 47.5 N | 125 W | 22 | 11 | 11 | 11 | 22 | 22 | 0 | 0 |
| 50 N | 115 W | 5 | 6 | 6 | 6 | 10 | 13 | 36 | 18 |
| 50 N | 117.5 W | 6 | 6 | 5 | 7 | 5 | 9 | 46 | 17 |
| 50 N | 120 W | 2 | 3 | 4 | 4 | 11 | 15 | 44 | 16 |
| 50 N | 122.5 W | 3 | 4 | 2 | 7 | 11 | 16 | 33 | 23 |
| 50 N | 125 W | 14 | 6 | 4 | 5 | 5 | 11 | 16 | 39 |
| 52.5 N | 115 W | 3 | 1 | 3 | 12 | 19 | 20 | 28 | 14 |
| 52.5 N | 117.5 W | 1 | 2 | 2 | 11 | 17 | 21 | 36 | 10 |
| 52.5 N | 120 W | 3 | 3 | 5 | 8 | 11 | 16 | 33 | 22 |
| 52.5 N | 122.5 W | 6 | 3 | 6 | 5 | 11 | 15 | 29 | 25 |
| 52.5 N | 125 W | 14 | 8 | 7 | 9 | 5 | 11 | 12 | 35 |
| 52.5 N | 127.5 W | 14 | 5 | 5 | 5 | 14 | 13 | 13 | 32 |
| 55 N | 115 W | 2 | 8 | 5 | 14 | 14 | 11 | 26 | 19 |
| 55 N | 117.5 W | 4 | 3 | 6 | 12 | 14 | 16 | 27 | 17 |
| 55 N | 120 W | 6 | 2 | 2 | 18 | 12 | 13 | 31 | 16 |
| 55 N | 122.5 W | 6 | 4 | 7 | 8 | 9 | 9 | 29 | 28 |
| 55 N | 125 W | 12 | 5 | 5 | 9 | 6 | 7 | 18 | 38 |
| 55 N | 127.5 W | 22 | 10 | 10 | 5 | 3 | 2 | 11 | 37 |
| 55 N | 130 W | 30 | 4 | 15 | 0 | 9 | 11 | 9 | 22 |
| 55 N | 132.5 W | 20 | 7 | 7 | 7 | 11 | 15 | 11 | 24 |
| 57.5 N | 115 W | 3 | 9 | 10 | 12 | 24 | 15 | 15 | 12 |
| 57.5 N | 117.5 W | 8 | 8 | 6 | 12 | 20 | 18 | 18 | 10 |
| 57.5 N | 120 W | 6 | 4 | 2 | 9 | 11 | 12 | 27 | 30 |
| 57.5 N | 122.5 W | 7 | 5 | 3 | 7 | 8 | 12 | 31 | 26 |
| 57.5 N | 125 W | 10 | 7 | 7 | 7 | 7 | 10 | 21 | 31 |
| 57.5 N | 127.5 W | 14 | 0 | 7 | 10 | 3 | 10 | 31 | 24 |
| 57.5 N | 130 W | 14 | 11 | 11 | 9 | 9 | 11 | 13 | 24 |
| 57.5 N | 132.5 W | 12 | 6 | 5 | 9 | 18 | 13 | 17 | 20 |
| 60 N | 115 W | 4 | 5 | 5 | 2 | 16 | 39 | 18 | 11 |
| 60 N | 117.5 W | 6 | 9 | 6 | 6 | 20 | 15 | 30 | 8 |
| 60 N | 120 W | 8 | 10 | 10 | 6 | 12 | 13 | 25 | 16 |
| 60 N | 122.5 W | 7 | 7 | 3 | 6 | 7 | 15 | 39 | 16 |
| 60 N | 125 W | 5 | 5 | 4 | 6 | 7 | 16 | 39 | 18 |
| 60 N | 127.5 W | 8 | 8 | 6 | 10 | 8 | 9 | 30 | 21 |
| 60 N | 130 W | 5 | 2 | 7 | 7 | 15 | 15 | 34 | 15 |
| 60 N | 132.5 W | 10 | 6 | 19 | 10 | 16 | 13 | 13 | 13 |
| 60 N | 135 W | 6 | 3 | 16 | 10 | 26 | 10 | 16 | 13 |

**Appendix 1 b: Average wind speed in each direction:**

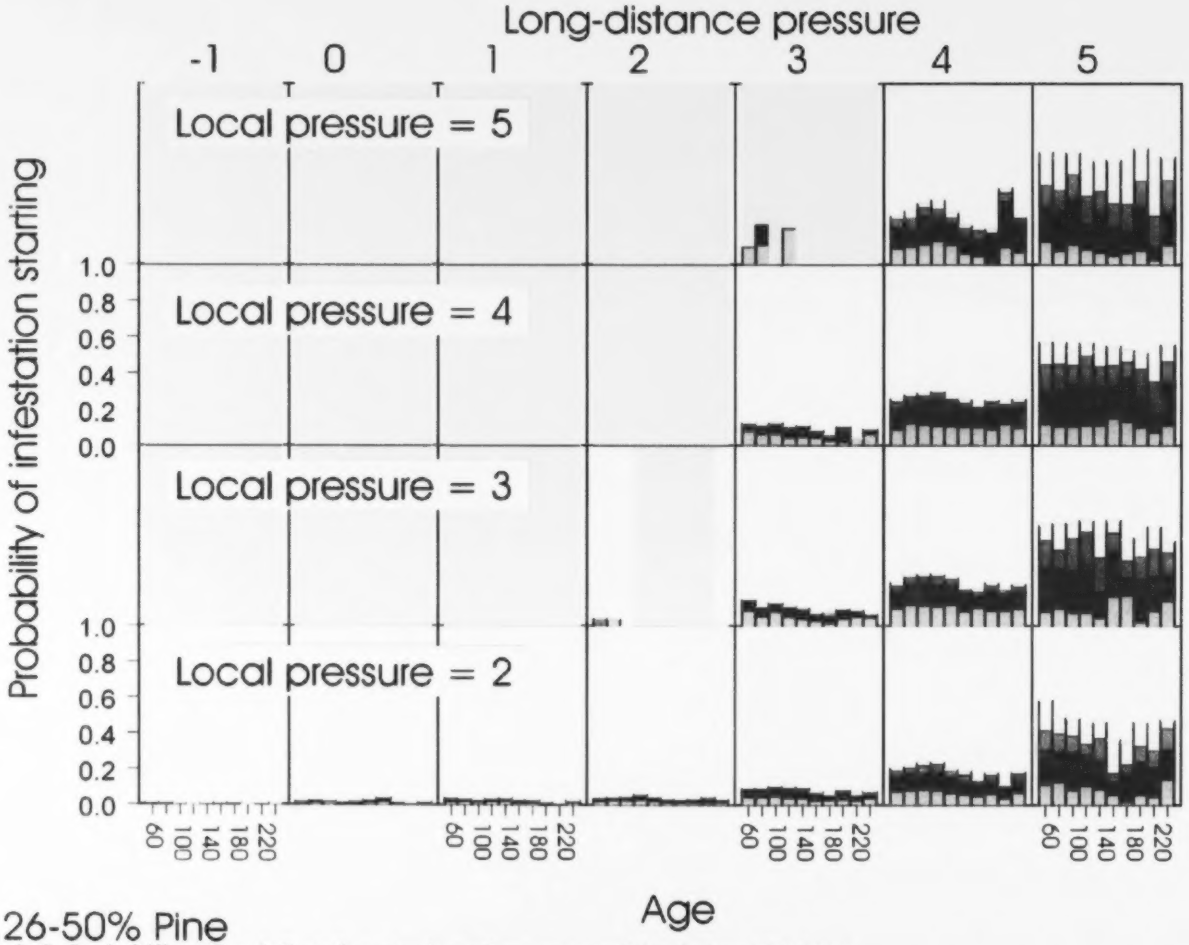
| Latitude | Longitude | N | NE | E | SE | S | SW | W | NW |
|---|---|---|---|---|---|---|---|---|---|
| 47.5 N | 122.5 W | 3.8 | 2.9 | 3.6 | 2.3 | 2.8 | 2.5 | 2.5 | 4.0 |
| 47.5 N | 125 W | 3.5 | 2.1 | 0.7 | 3.6 | 2.2 | 2.5 | 0.0 | 0.0 |
| 50 N | 115 W | 2.4 | 2.0 | 2.4 | 3.1 | 2.4 | 3.1 | 3.9 | 3.5 |
| 50 N | 117.5 W | 1.9 | 1.9 | 2.6 | 2.5 | 2.2 | 3.3 | 4.2 | 3.3 |
| 50 N | 120 W | 1.8 | 2.5 | 2.2 | 2.4 | 2.5 | 3.6 | 3.8 | 3.4 |
| 50 N | 122.5 W | 1.8 | 3.2 | 4.6 | 2.7 | 2.4 | 2.5 | 3.6 | 3.5 |
| 50 N | 125 W | 4.1 | 4.2 | 2.5 | 2.8 | 3.1 | 3.9 | 3.7 | 4.7 |
| 52.5 N | 115 W | 2.4 | 1.3 | 1.9 | 5.0 | 4.1 | 3.4 | 5.2 | 3.8 |
| 52.5 N | 117.5 W | 2.0 | 0.9 | 2.7 | 4.3 | 3.2 | 3.3 | 4.8 | 2.6 |
| 52.5 N | 120 W | 2.4 | 2.1 | 2.2 | 2.9 | 2.7 | 3.5 | 4.4 | 3.8 |
| 52.5 N | 122.5 W | 2.4 | 1.6 | 2.0 | 2.5 | 2.4 | 3.2 | 3.5 | 3.4 |
| 52.5 N | 125 W | 3.1 | 2.2 | 2.8 | 3.2 | 2.4 | 3.2 | 2.7 | 4.1 |
| 52.5 N | 127.5 W | 3.8 | 3.2 | 2.8 | 3.0 | 5.5 | 5.6 | 4.1 | 4.6 |
| 55 N | 115 W | 2.4 | 4.6 | 3.5 | 4.3 | 5.4 | 3.6 | 5.5 | 4.2 |
| 55 N | 117.5 W | 3.6 | 3.3 | 3.5 | 3.8 | 4.7 | 3.6 | 5.7 | 4.5 |
| 55 N | 120 W | 4.0 | 2.8 | 4.5 | 3.1 | 3.3 | 2.7 | 4.5 | 5.5 |
| 55 N | 122.5 W | 2.5 | 2.7 | 2.9 | 3.0 | 2.2 | 2.7 | 4.2 | 4.4 |
| 55 N | 125 W | 3.3 | 2.5 | 3.4 | 3.0 | 2.2 | 3.2 | 4.0 | 4.2 |
| 55 N | 127.5 W | 4.5 | 3.6 | 4.7 | 3.8 | 2.4 | 2.7 | 4.2 | 4.8 |
| 55 N | 130 W | 4.9 | 5.2 | 4.9 | 0.0 | 3.2 | 7.0 | 5.4 | 4.8 |
| 55 N | 132.5 W | 7.3 | 4.9 | 5.9 | 2.7 | 6.1 | 6.8 | 3.1 | 6.5 |
| 57.5 N | 115 W | 5.9 | 6.1 | 5.4 | 4.2 | 4.2 | 4.7 | 6.0 | 5.0 |
| 57.5 N | 117.5 W | 4.2 | 5.8 | 3.3 | 3.9 | 4.0 | 3.8 | 5.7 | 5.3 |
| 57.5 N | 120 W | 4.2 | 3.8 | 2.7 | 3.4 | 3.4 | 3.2 | 4.6 | 5.2 |
| 57.5 N | 122.5 W | 3.5 | 4.0 | 4.2 | 3.2 | 2.2 | 3.3 | 4.4 | 5.1 |
| 57.5 N | 125 W | 4.0 | 6.5 | 2.9 | 2.9 | 2.7 | 2.1 | 4.1 | 3.7 |
| 57.5 N | 127.5 W | 5.1 | 0.0 | 2.7 | 3.6 | 7.2 | 2.9 | 3.7 | 4.0 |
| 57.5 N | 130 W | 3.5 | 3.6 | 3.1 | 4.5 | 4.5 | 3.1 | 3.6 | 4.2 |
| 57.5 N | 132.5 W | 4.1 | 3.1 | 2.8 | 3.9 | 6.1 | 5.0 | 4.5 | 4.2 |
| 60 N | 115 W | 5.9 | 3.9 | 4.5 | 5.2 | 4.7 | 6.7 | 6.2 | 3.7 |
| 60 N | 117.5 W | 3.9 | 4.4 | 9.8 | 3.8 | 4.4 | 4.1 | 4.9 | 5.0 |
| 60 N | 120 W | 3.7 | 5.1 | 4.0 | 2.9 | 4.4 | 4.3 | 5.9 | 5.6 |
| 60 N | 122.5 W | 3.3 | 3.1 | 2.8 | 2.5 | 2.3 | 4.1 | 5.8 | 5.5 |
| 60 N | 125 W | 3.1 | 3.0 | 2.7 | 2.9 | 2.6 | 4.1 | 5.8 | 4.7 |
| 60 N | 127.5 W | 3.6 | 3.5 | 2.5 | 3.0 | 3.5 | 3.2 | 4.9 | 5.3 |
| 60 N | 130 W | 2.8 | 2.6 | 3.4 | 3.7 | 3.6 | 3.9 | 5.5 | 6.8 |
| 60 N | 132.5 W | 2.6 | 2.0 | 2.4 | 4.1 | 2.9 | 3.1 | 1.8 | 2.9 |
| 60 N | 135 W | 2.6 | 2.3 | 2.2 | 3.4 | 2.8 | 3.2 | 2.2 | 3.2 |

## Appendix 2 Probabilities that drive the infestation start sub-model.

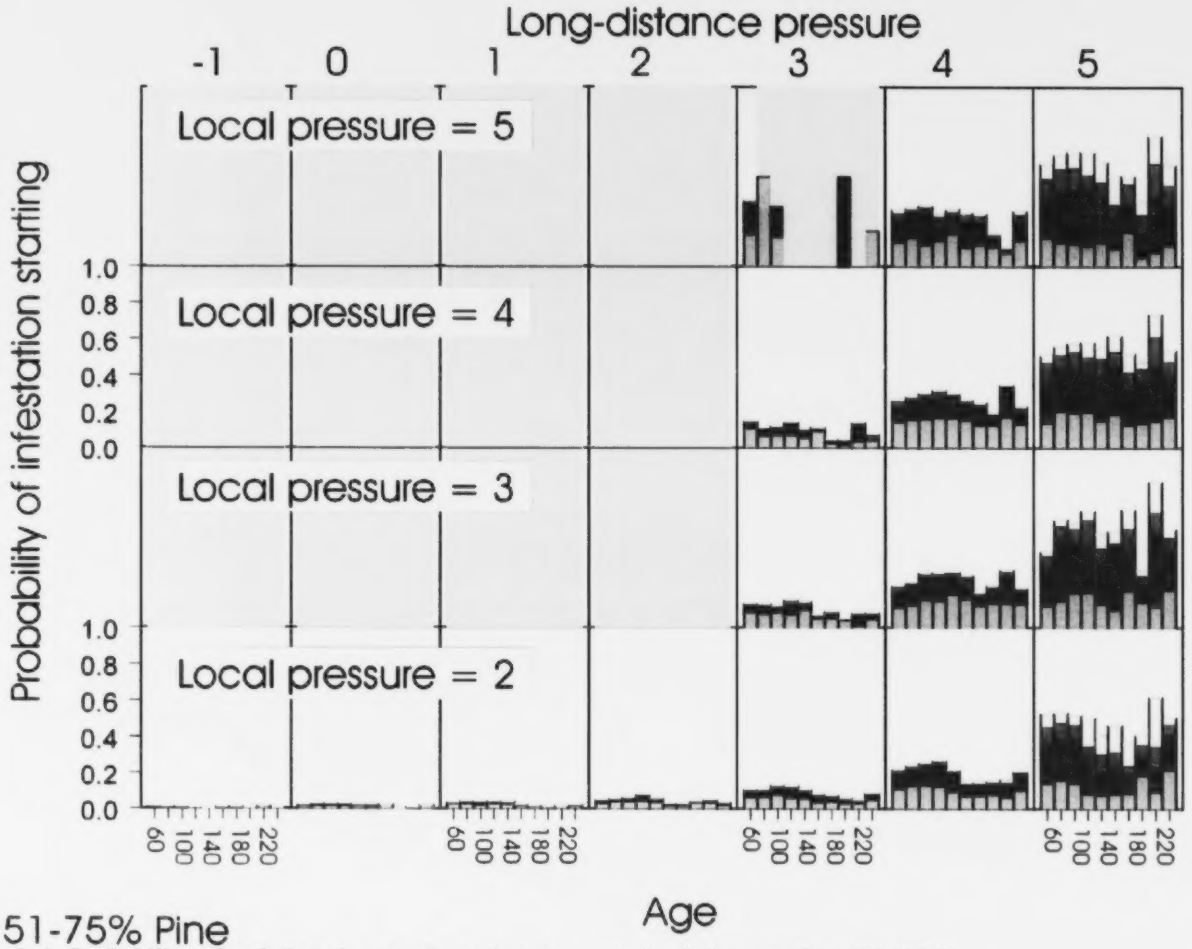
In the stacked bars, colour indicates infestation severity: yellow is severe; red is moderate; blue is low; and green is endemic. Probabilities are from transitions observed in the aerial survey data between 1999 and 2004. Not all combinations of all factors in the start sub-model were observed over that period. Light grey indicates that less than 10 examples of this condition were observed between 1999 and 2004.



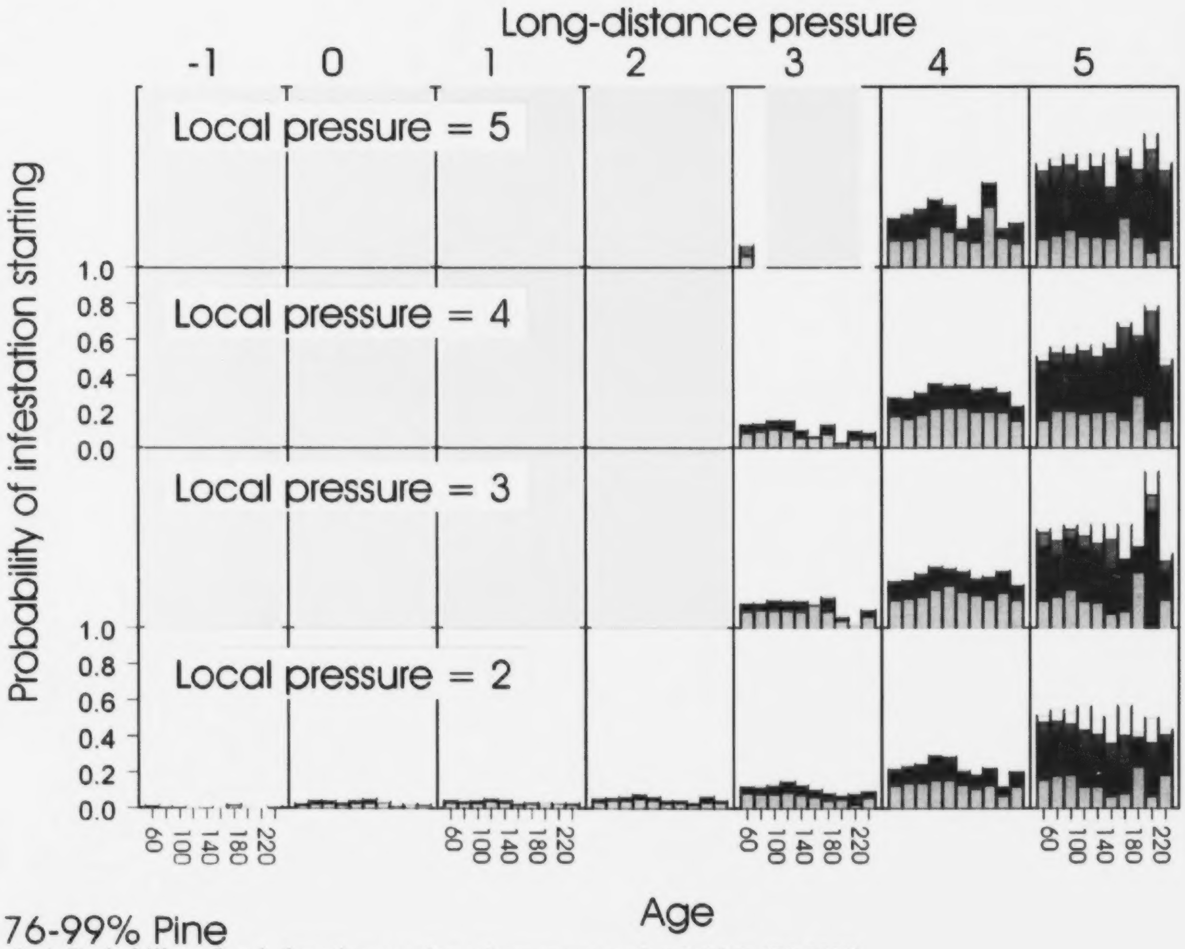
a2_1: Probability of an infestation starting where percent pine is very low (1-25%).



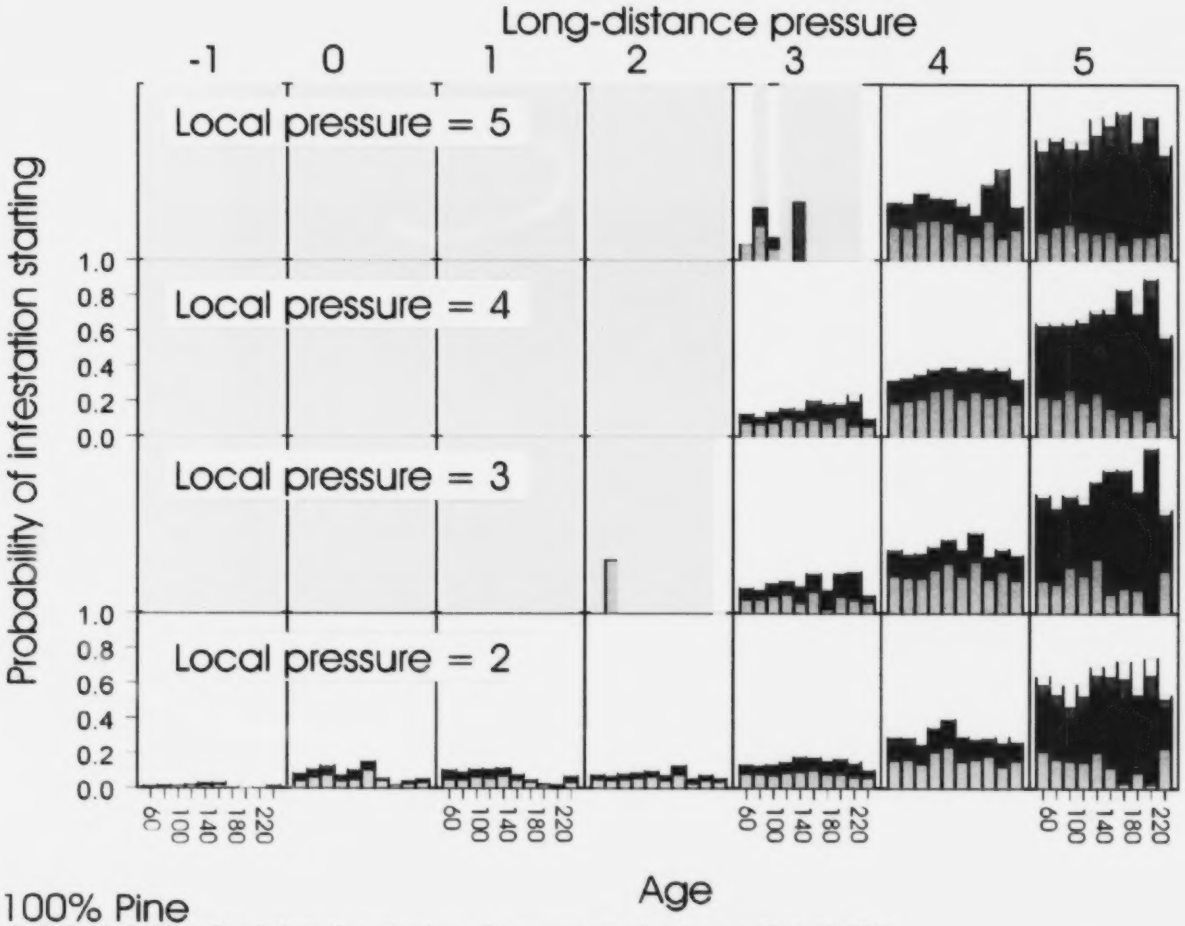
a2_2: Probability of an infestation starting where percent pine is low (26-50%).



a2_3: Probability of an infestation starting where percent pine is intermediate (51-75%).



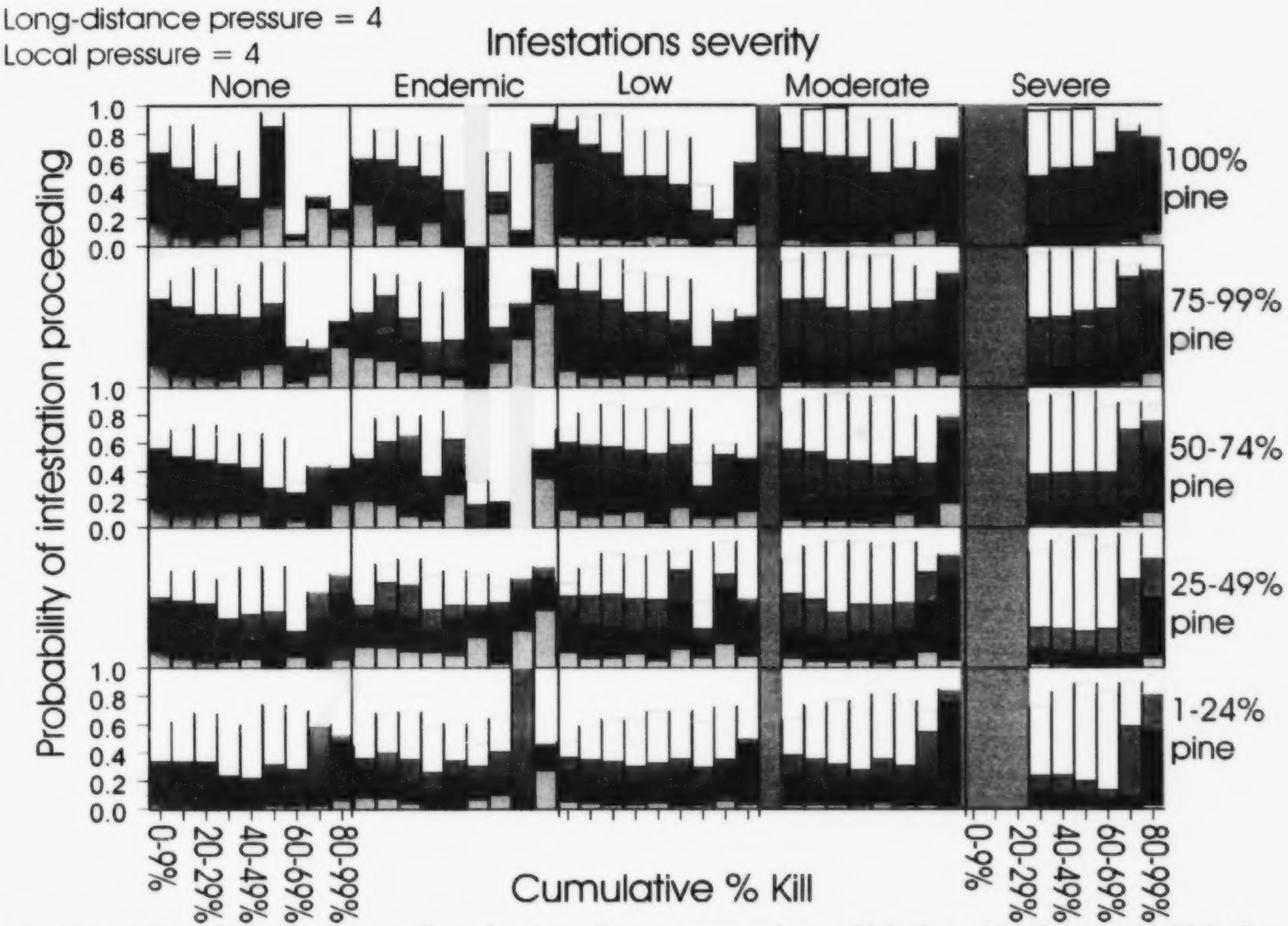
a2_4: Probability of an infestation starting where percent pine is high (76-99%).



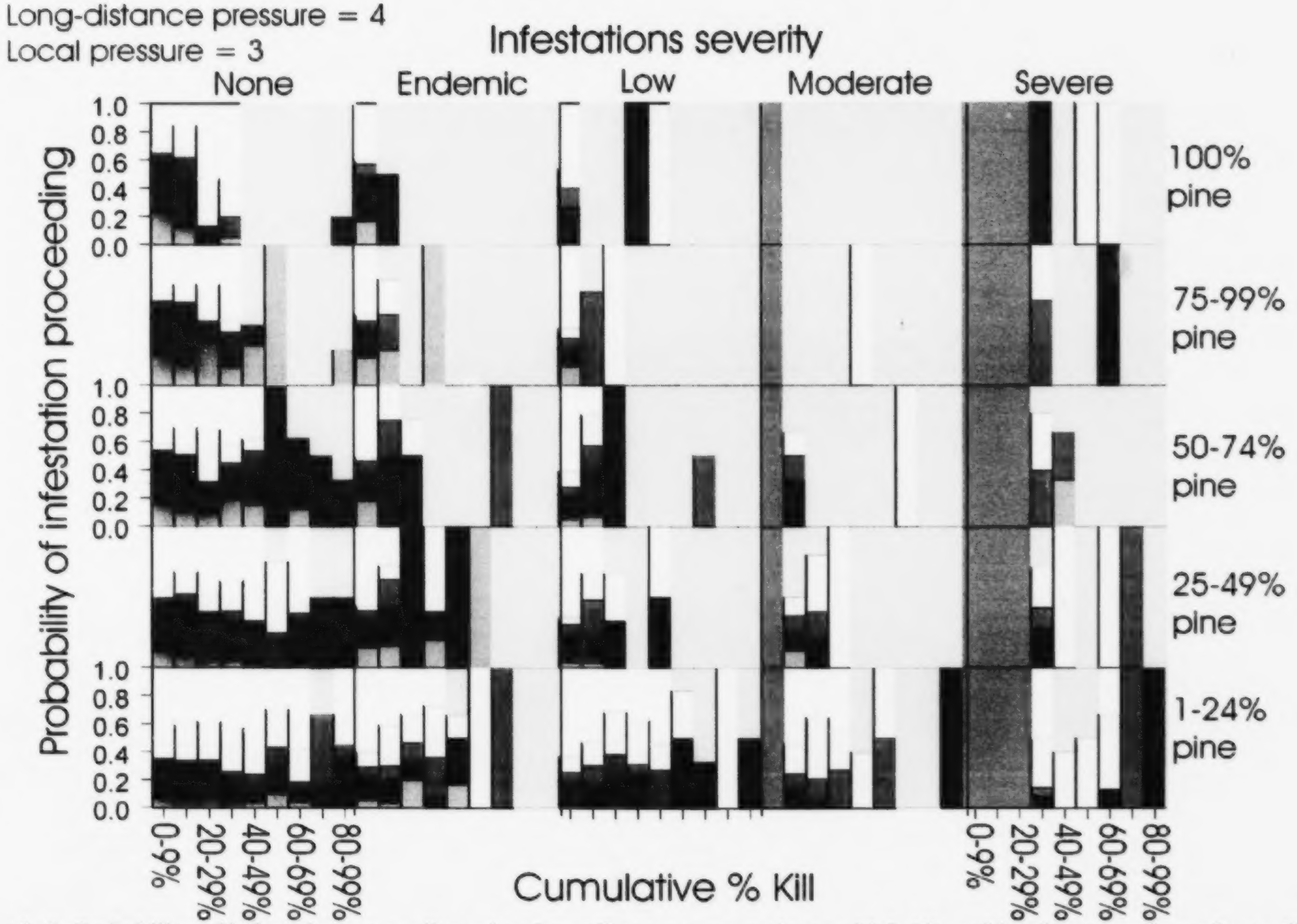
a2_5: Probability of an infestation starting where percent pine is very high (100%).

## Appendix 3 Probabilities that drive the infestation progress model.

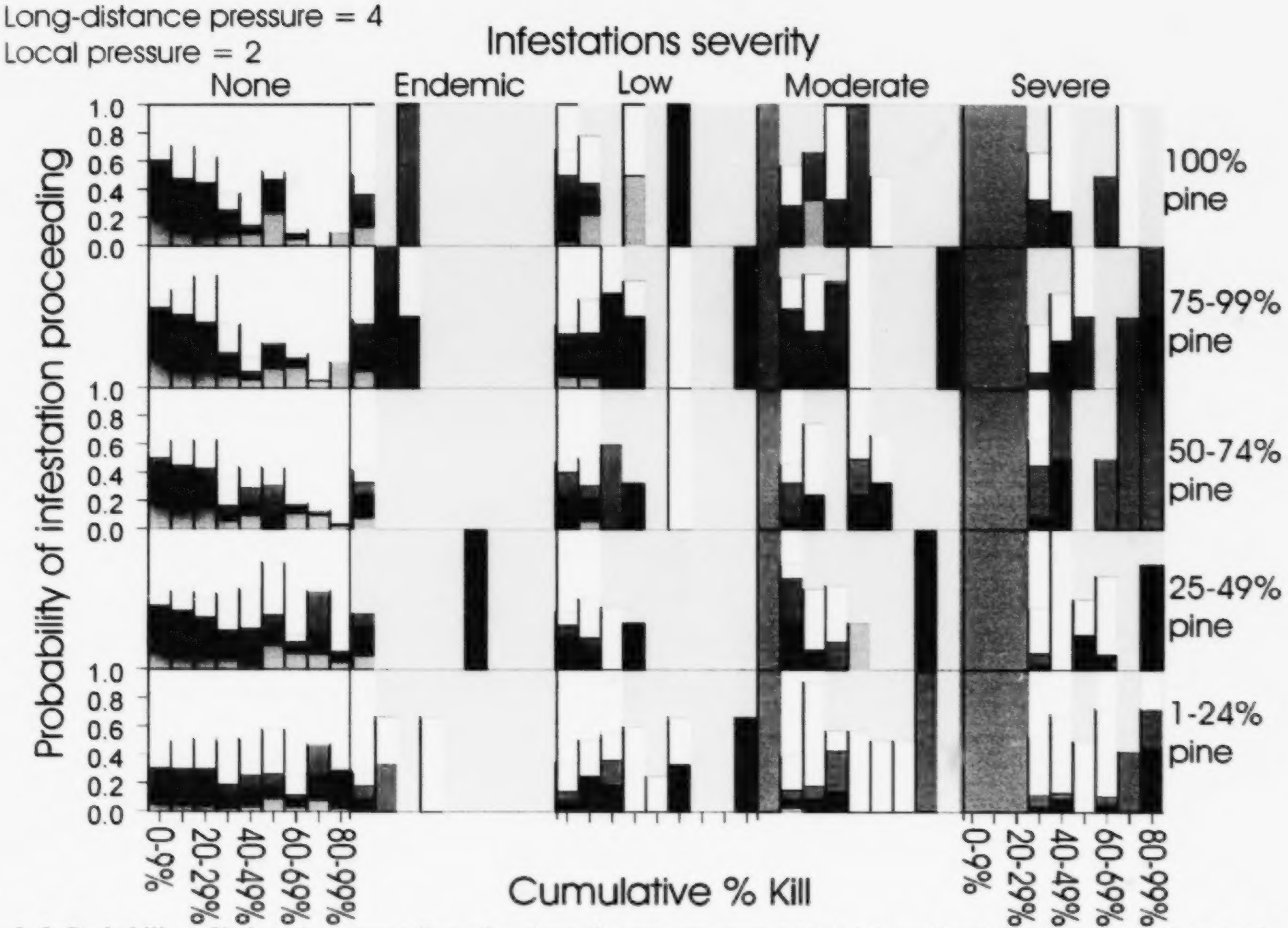
In the stacked bars, colour indicates infestation severity: yellow is severe; red is moderate; blue is low; and green is endemic. Probabilities are from transitions observed in the aerial survey data between 1999 and 2004. Not *all* combinations of *all* factors in the progress model were observed over that period. Some combinations are in fact logically impossible (coloured dark grey). Light grey indicates that less than 10 examples of this condition were observed between 1999 and 2004.



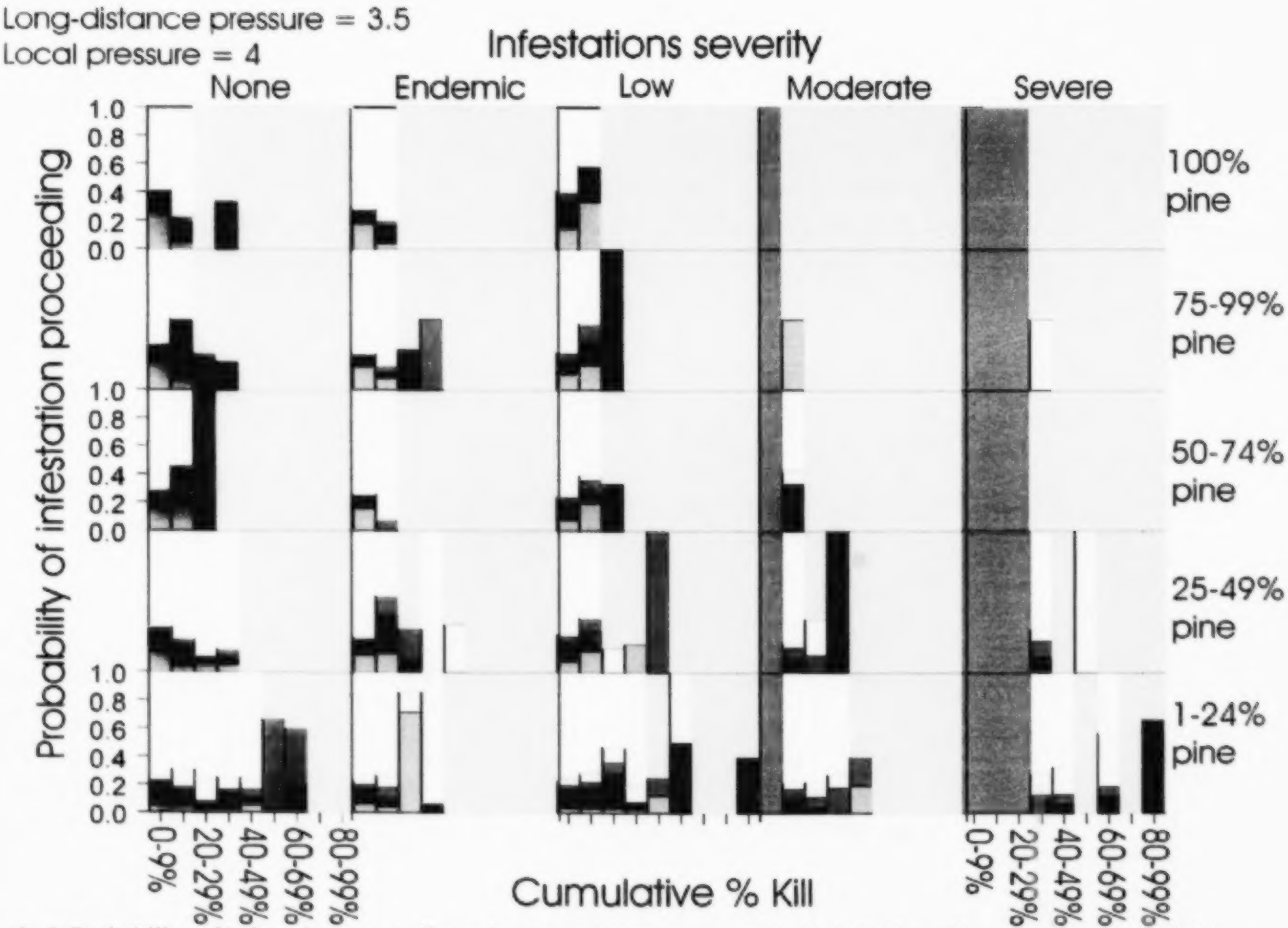
a3_1: Probability of infestation proceeding when long-distance pressure is very high (4), and local pressure is high (4).



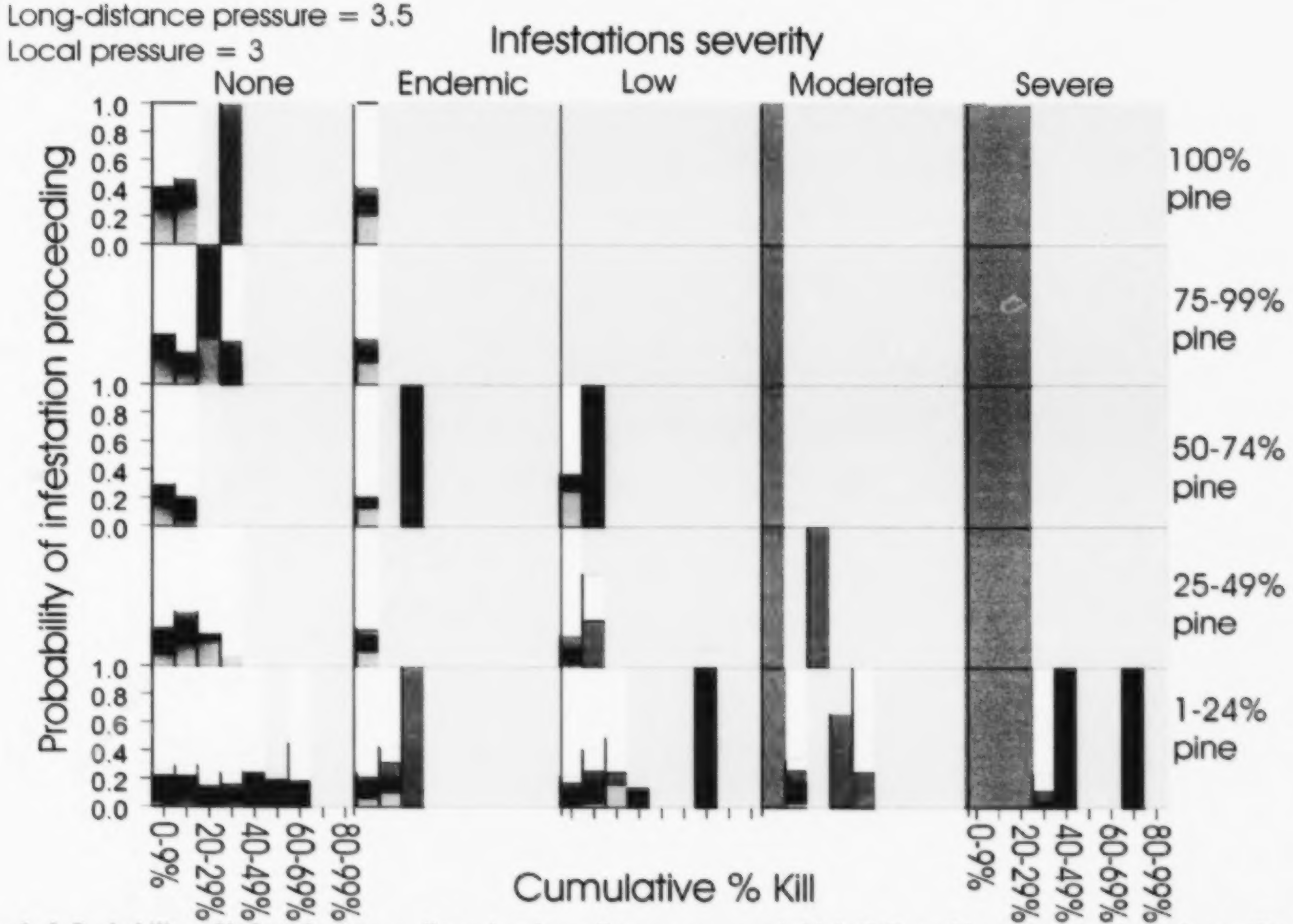
a3_2: Probability of infestation proceeding when long-distance pressure is very high (4), and local pressure is moderate (3).



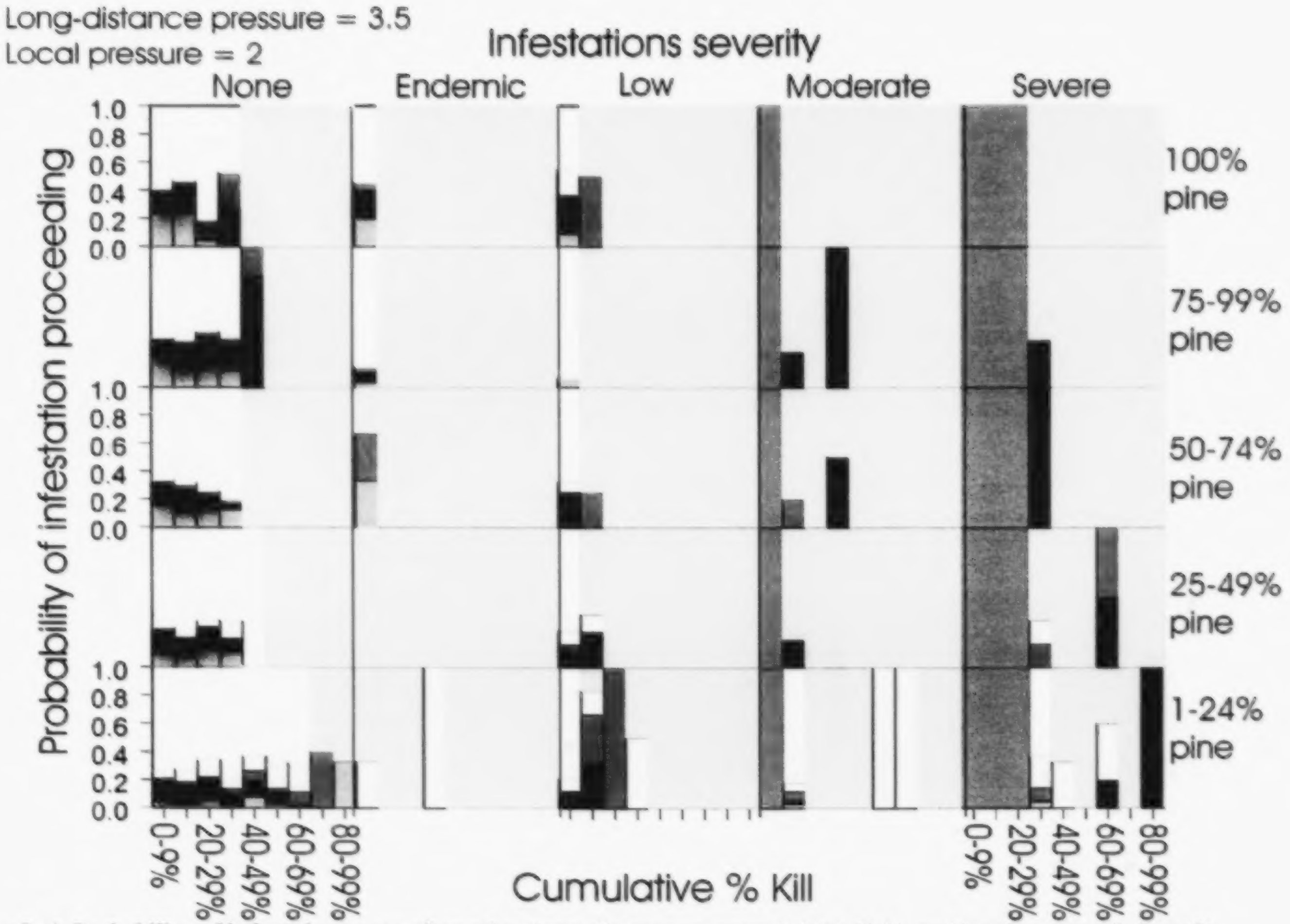
a3_3: Probability of infestation proceeding when long-distance pressure is high (4), and local beetle pressure is low (2).



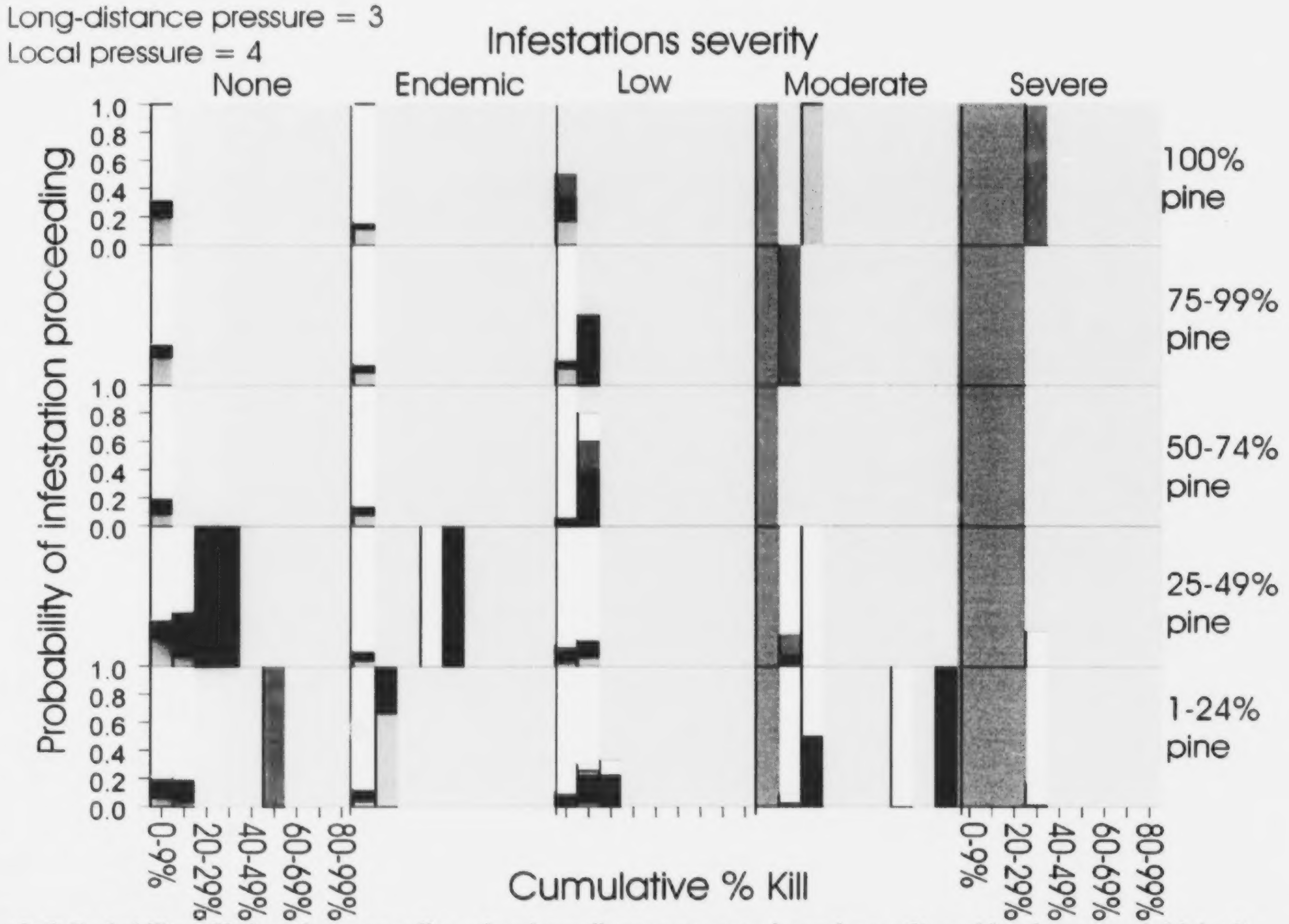
a3_4: Probability of infestation proceeding when long-distance pressure is high (3.5), and local pressure is high (4).



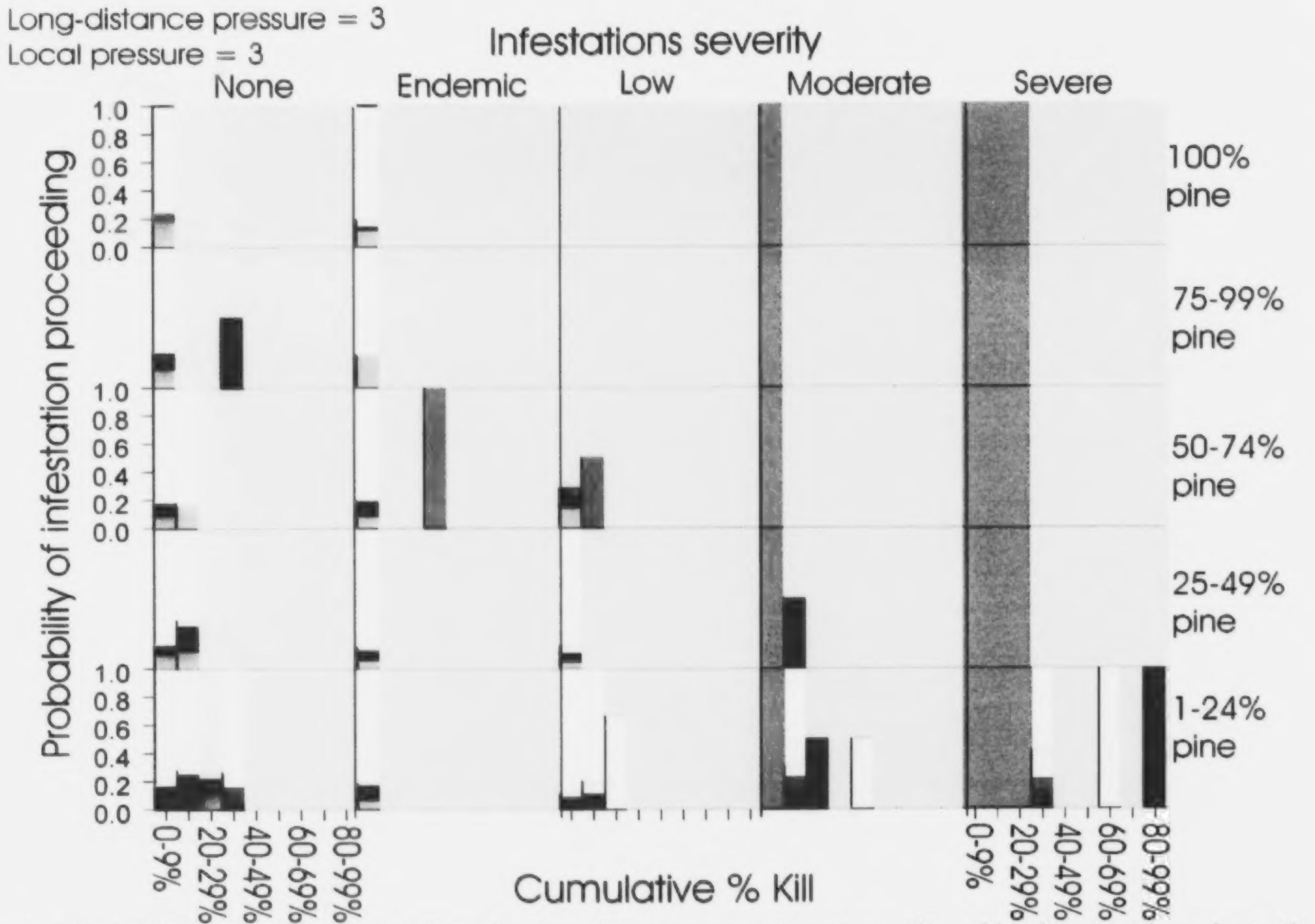
a3_5: Probability of infestation proceeding when long-distance pressure is high (3.5), and local pressure is moderate (3).



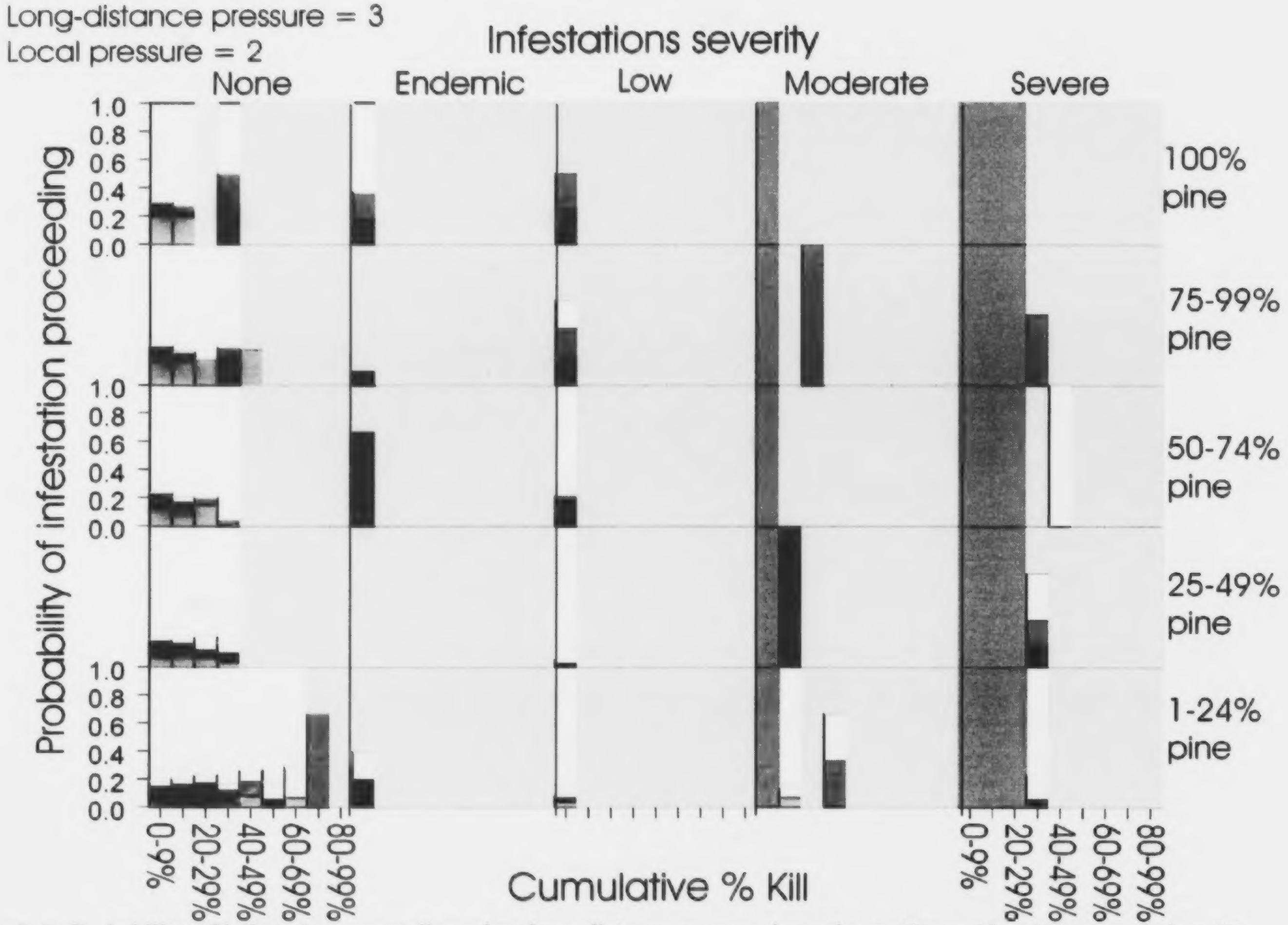
a3_6: Probability of infestation proceeding when long-distance pressure is high (3.5), and local pressure is low (2).



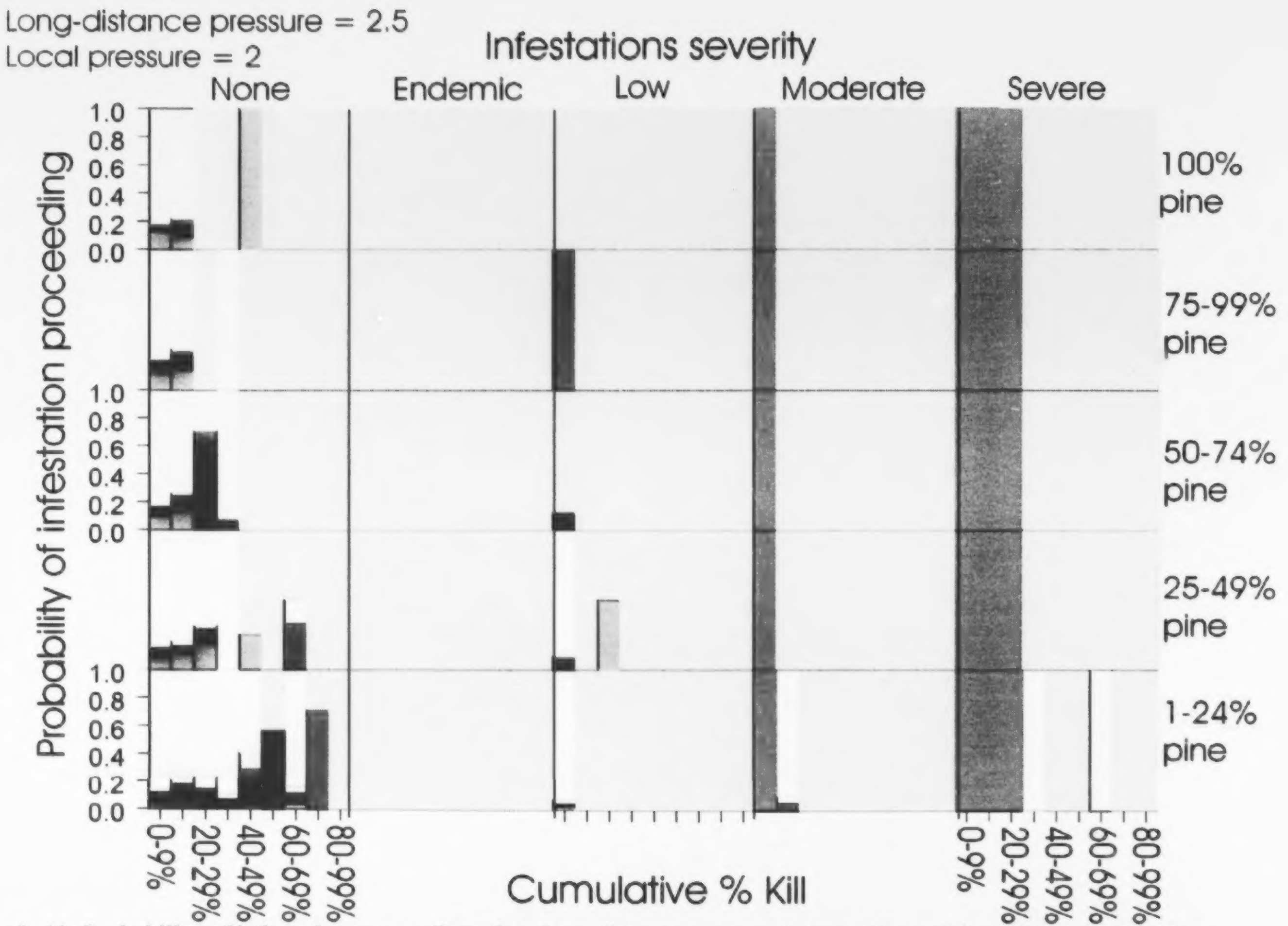
a3_7: Probability of infestation proceeding when long-distance pressure is moderate (3), and local pressure is high (4).



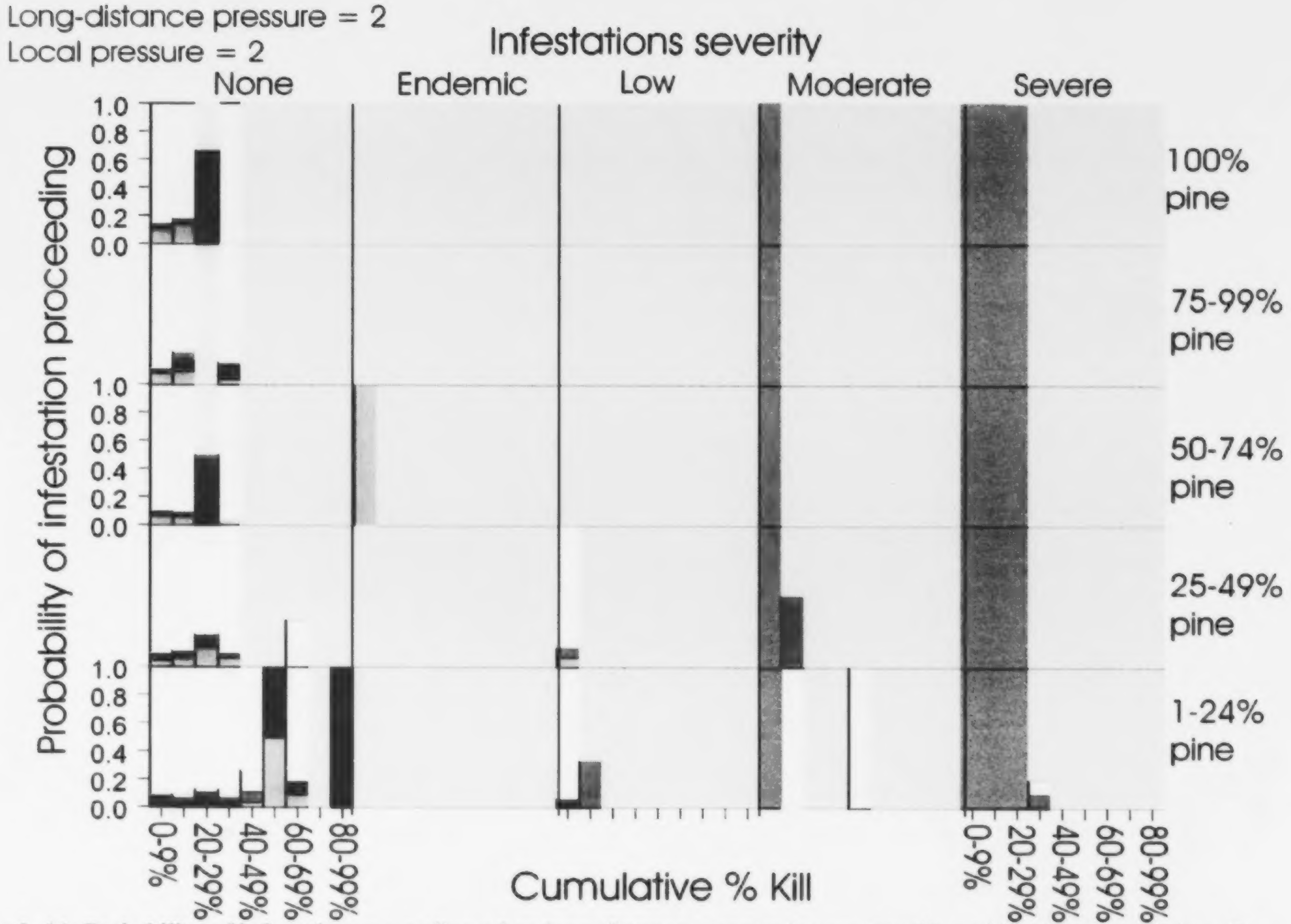
a3_8: Probability of infestation proceeding when long-distance pressure is moderate (3), and local pressure is moderate (3).



a3_9: Probability of infestation proceeding when long-distance pressure is moderate (3), and local pressure is low (2).



a3_10: Probability of infestation proceeding when long-distance pressure is low (2.5), and local beetle is low (2).



a3_11: Probability of infestation proceeding when long-distance pressure is very low (2), and local pressure is low (2).

# Provincial Level Projection of the Current Mountain Pine Beetle Outbreak:

## An
## Overview of the Model (BCMPBv.2)
## and
## Results of Year 2 of the Project

### Appendix 4. Details of the Shelf-Life Model

*Supported by the*
*Mountain Pine Beetle Initiative of the Canadian Forest Service*
*and the BC Forest Service*

Canada

BRITISH
COLUMBIA

**Marvin Eng, Research Branch, BC Forest Service**

**December 2004**

We define shelf life as "the length of time after death that a tree will be useable for a given product." Therefore, "shelf-life" is product specific and differs for sawlogs, OSB, pulp, bio fuels, woodpecker habitat, etc. A corollary of this concept is that the actual volume of timber in an MPB killed stand may remain the same for some significant length of time but it will change in character as time progresses.

A narrative version of our conceptual model of shelf-life is:

- There is a relationship between time since death and applicable products for (stands of) pine trees killed by MPB.
- Beetle killed logs will be useable as sawlogs (dimensional lumber) during the winter and summer harvesting seasons immediately following their death.
- For (X) subsequent years they loose their bark and begin to deteriorate in quality (with some minor checking) but essentially the entire volume will continue to be useable as sawlogs.
- From (X) to (N) years, the volume that can be used as sawlogs will decline in a linear fashion to the point where none of it is useable for dimensional lumber.
- From (X) to (M) some portion of the volume, in addition to that useable as sawlogs, will be useable for "alternative purposes", for example, chips, biofuel, etc. The decline in the amount of total usable wood (from (Y > X) to (M) years) will occur in a linear fashion.
- (N) and (M) will vary depending on the biogeoclimatic subzone and will be shorter in duration in wetter subzones and longer in dries subzones.

We model a conservative[1], optimistic and pessimistic set of shelf-life assumptions as follows:

Conservative

All volume available for all products for **3 years** after death.

| Subzones | Time to complete deterioration of sawlog volume | Time to complete deterioration of "alternative" volume |
|---|---|---|
| Dry | 7 | 15 |
| Moist | 6 | 13 |
| Wet | 5 | 10 |

Note that this means that after 4 years in a moist subzone two thirds of the volume would be available for sawlogs.

---

[1] based on information used in Thrower, J.S. 2003. Shelf-life tables and ingress assumptions for the Vanderhoof IFPA second innovative analysis. Vanderhoof IFPA TFP-004

Pessimistic

All volume available for all products for **2 years** after death.

| Subzones | Time to complete deterioration of sawlog volume | Time to complete deterioration of "alternative" volume |
|---|---|---|
| Dry | 5 | 10 |
| Moist | 4 | 8 |
| Wet | 3 | 5 |

Note that this means that after 3 years in a moist subzone one half of the volume would be available for sawlogs.

Optimistic

All volume available for all products for **4 years** after death.

| Subzones | Time to complete deterioration of sawlog volume | Time to complete deterioration of "alternative" volume |
|---|---|---|
| Dry | 15 | 25 |
| Moist | 8 | 18 |
| Wet | 7 | 15 |

Note that this means that after 6 years in a moist subzone two thirds of the volume would be available for sawlogs.

These relationships are shown graphically in Figure 1 where "alternative" volumes are labelled "chips".

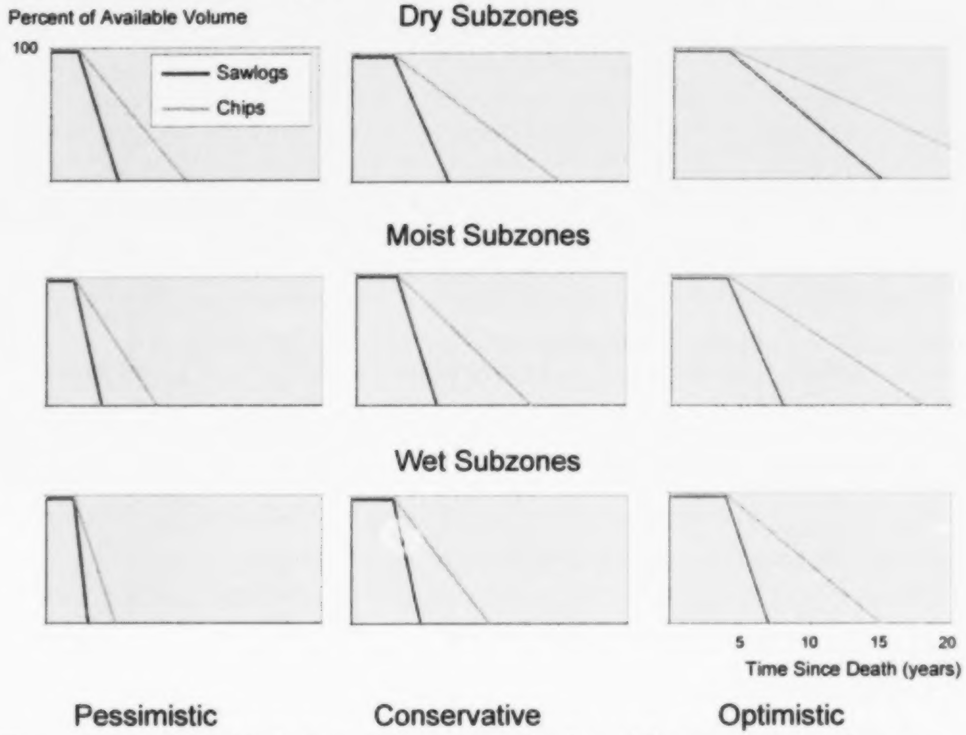


Figure 1. Relationship between time since death and the amount of volume available for the sawlog and "alternative" (chip) industries in dry, moist and wet subzones under pessimistic, conservative and optimistic assumptions.

In order to implement this conceptual model we developed a process for grouping subzones into dry, moist and wet categories that would correspond to slow, moderate and fast degradation rates of timber quality

In general it is assumed that the rate at which standing fiber will degrade from sawlog to chips and then to unmerchantable bears some relationship to the moisture regime of the climate. Degradation is the result of 2 factors; checking and sap rot. Checking is assumed to be more severe and more rapid in moister climates because ring width is positively correlated with growing season moisture and narrow rings are denser and hence less susceptible to checking. In addition, it is believed that more checking may occur in moister climates because shrinkage may be more severe as the wood looses moisture and winter freeze thaw cycles may be more pronounced. Sap rot is assumed to occur more rapidly in wetter climates (particularly growing season moisture) because moisture is an important determinant of the ability of those fungi to grow and reproduce.

The relationships described above are relatively poorly understood. For that reason we rely on a categorization of Biogeoclimatic Subzones into 3 groups; slow, moderate and rapid degradation rates. This is done rather than using actual climatic maps because the Biogeoclimatic Subzones integrate a number of climatic variables and because forest practitioners are familiar with the zoning and can provide input and criticism based on local knowledge.

In order to implement the concepts described above we did the following:

- Obtain data from and overlay Biogeoclimatic Subzones on growing season (May to September) and total annual precipitation data (based on PRISM Climate Surfaces).
- Overlay Biogeoclimatic Subzones on percent of timber volume that is pine.
- To simplify the process, eliminate some subzones from the ranking procedure for one of three reasons:
    - Those that need not be considered because they are in non-susceptible climatic zones (AT, CWH, MH, CDF, BWBS and SWB – see BCMPB documentation for rationale).
    - Those that need not be considered because pine volume is a minor (<10%) component of the total volume or they are a parkland or woodland subzone.
    - Those that could not be considered because climatic data was not available (newly mapped).
- Rank the remaining subzones based on total annual precipitation and growing season precipitation. For each ranking divide the subzones into 3 groups based on:
    - An equal number of subzones in each group
    - An equal area in each group
    - One third of the range of the precipitation occurring in each group.
- For each variable (total and growing season precipitation) compare the 3 ranking and assign an overall rank where 2 or 3 of the individual ranks agree. This worked for all but one subzone in total precipitation, which received 3 different ranks.
- Compare the overall ranks for both variables and assign a final rank where both agree. Where there is disagreement use expert (Del Meidinger) knowledge of the climates of the subzones to resolve the difference.
- For completeness:
    - Assign a rating to low percentage pine subzones based on the amount of summer precipitation relative to other ranked zones
    - Assign a rating to subzones with no climate data based on similarity with other ranked zones.
    - Assign moderate degrade rate to all subzones in climatically unsuitable areas.

The results of this process are shown in the map in Figure 2 and in detail in Table 2

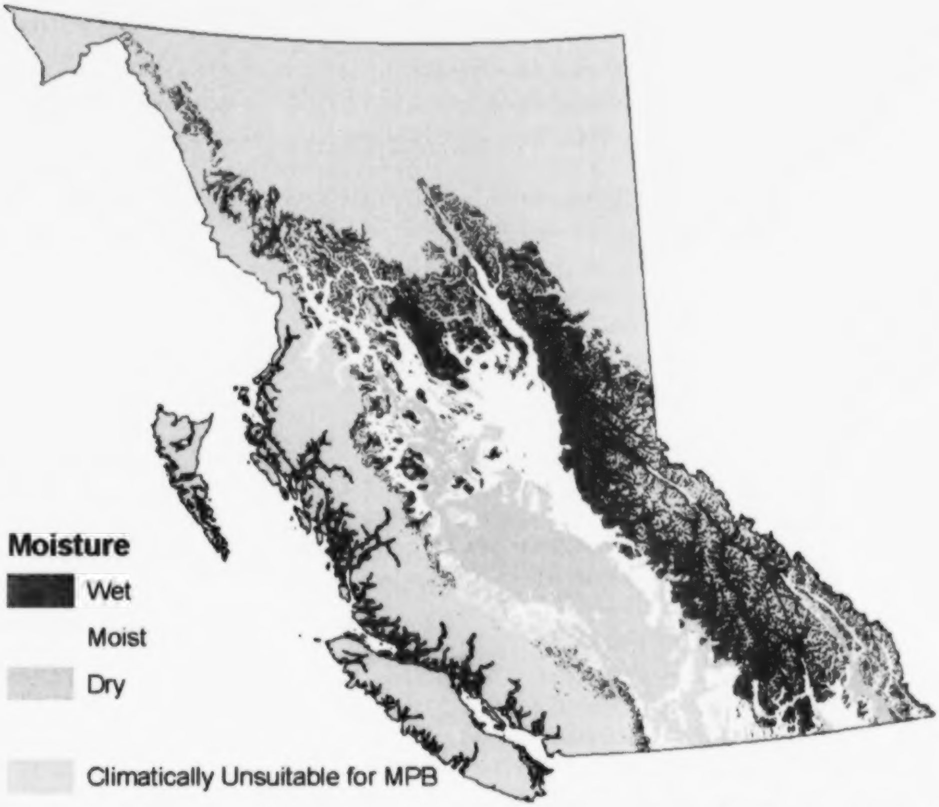

Moisture
Wet
Moist
Dry
Climatically Unsuitable for MPB

Figure 2. Categorization of subzones into moisture regimes for the purpose of estimating fibre degradation rates.

**Table 1 Moisture rankings by Biogeoclimatic subzone (colour coding indicates decision criteria provided at the end of the table).**

| | | | Precipitation (mm) | |
|---|---|---|---|---|
| Categories | Subzone | Moisture Ranking | Total | Growing Season |
| In | SBS wk | ■ | 766 | 327 |
| Pine < 10 % | SBS vk | wet | 1,037 | 403 |
| Pine < 10 % | ICH wk | wet | 1,064 | 400 |
| In | ICH wc | wet | 1,074 | 340 |
| Pine < 10 % | ICH vk | wet | 1,257 | 433 |
| Pine < 10 % | ICH vc | ■ | 868 | 313 |
| In | ICH mw | wet | 913 | 334 |
| In | ICH mm | wet | 894 | 355 |
| No Data | ESSFwvp | wet | #N/A | #N/A |
| Pine < 10 % | ESSFwv | wet | 1,103 | 382 |
| No Data | ESSFwmw | wet | #N/A | #N/A |
| Parkland | ESSFwmp | wet | 1,305 | 426 |
| In | ESSFwm | wet | 1,211 | 393 |
| Parkland | ESSFwkp | wet | 967 | 410 |
| Pine < 10 % | ESSFwk | wet | 1,162 | 463 |
| No Data | ESSFwcw | wet | #N/A | #N/A |
| Pine < 10 % | ESSFwcp | wet | 1,514 | 498 |
| Pine < 10 % | ESSFwc | wet | 1,267 | 458 |
| No Data | ESSFvvp | wet | #N/A | #N/A |
| No Data | ESSFvv | wet | #N/A | #N/A |
| Pine < 10 % | ESSFvcp | wet | 1,744 | 522 |
| Pine < 10 % | ESSFvc | wet | 1,617 | 498 |
| Pine < 10 % | ESSFmwp | wet | 1,732 | 407 |
| In | ESSFmw | wet | 1,565 | 357 |
| No Data | ESSFmvp | wet | #N/A | #N/A |
| In | ESSFmv | ■ | 728 | 349 |
| Pine < 10 % | ESSFmmp | wet | 1,340 | 397 |
| In | ESSFmm | wet | 1,201 | 483 |
| No Data | ESSFmkp | wet | #N/A | #N/A |
| Pine < 10 % | ESSFmk | wet | 1,650 | 394 |
| No Data | ESSFmcp | wet | #N/A | #N/A |
| In | ESSFmc | wet | 903 | 333 |
| Parkland | ESSFdkp | wet | 1,220 | 473 |
| In | ESSFdk | wet | 1,085 | 426 |
| In | SBS mw | moist | 647 | 313 |

| | | | | |
|---|---|---|---|---|
| In | SBS mm | moist | 724 | 324 |
| In | SBS mk | moist | 668 | 279 |
| Pine < 10 % | SBS mh | moist | 548 | 265 |
| In | SBS mc | moist | 644 | 267 |
| In | SBS dw | [redacted] | 588 | 271 |
| In | SBS dh | [redacted] | 739 | 312 |
| In | MS un | [redacted] | 1,203 | 284 |
| In | MS dv | [redacted] | 1,055 | 250 |
| In | MS dm | [redacted] | 672 | 256 |
| In | MS dk | [redacted] | 772 | 306 |
| In | ICH mk | moist | 712 | 295 |
| Pine < 10 % | ICH mc | moist | 832 | 327 |
| In | ICH dw | [redacted] | 792 | 270 |
| No Data | ICH dm | moist | #N/A | #N/A |
| In | ICH dk | moist | 690 | 287 |
| In | ESSFxv | [redacted] | 857 | 256 |
| Parkland | ESSFxcp | moist | 625 | 260 |
| In | ESSFxc | moist | 712 | 278 |
| Parkland | ESSFdvp | [redacted] | 677 | 191 |
| In | ESSFdv | [redacted] | 915 | 235 |
| No Data | ESSFdmw | moist | #N/A | #N/A |
| No Data | ESSFdmp | moist | #N/A | #N/A |
| No Data | ESSFdm | moist | #N/A | #N/A |
| No Data | ESSFdkw | moist | #N/A | #N/A |
| No Data | ESSFdcw | moist | #N/A | #N/A |
| Parkland | ESSFdcp | moist | 1,090 | 320 |
| In | ESSFdc | [redacted] | 833 | 316 |
| In | SBS un | dry | 624 | 236 |
| In | SBS dk | dry | 522 | 224 |
| In | SBPSxc | dry | 418 | 198 |
| In | SBPSmk | dry | 542 | 273 |
| In | SBPSmc | dry | 517 | 208 |
| In | SBPSdc | dry | 506 | 263 |
| In | PP xh | dry | 367 | 152 |
| In | PP dh | dry | 436 | 201 |
| In | MS xv | dry | 538 | 250 |
| In | MS xk | dry | 527 | 221 |
| In | MS dc | dry | 752 | 210 |
| In | IDF xw | dry | 351 | 174 |
| Pine < 10 % | IDF xm | dry | 396 | 215 |
| In | IDF xh | dry | 431 | 182 |
| In | IDF ww | dry | 998 | 216 |
| Pine < 10 % | IDF un | dry | 527 | 200 |

| | | | | |
|---|---|---|---|---|
| In | SBS mm | moist | 724 | 324 |
| In | SBS mk | moist | 668 | 279 |
| Pine < 10 % | SBS mh | moist | 548 | 265 |
| In | SBS mc | moist | 644 | 267 |
| In | SBS dw | ■ | 588 | 271 |
| In | SBS dh | | 739 | 312 |
| In | MS un | | 1,203 | 284 |
| In | MS dv | | 1,055 | 250 |
| In | MS dm | | 672 | 256 |
| In | MS dk | | 772 | 306 |
| In | ICH mk | moist | 712 | 295 |
| Pine < 10 % | ICH mc | moist | 832 | 327 |
| In | ICH dw | ■ | 792 | 270 |
| No Data | ICH dm | moist | #N/A | #N/A |
| In | ICH dk | moist | 690 | 287 |
| In | ESSFxv | ■ | 857 | 256 |
| Parkland | ESSFxcp | moist | 625 | 260 |
| In | ESSFxc | moist | 712 | 278 |
| Parkland | ESSFdvp | ■ | 677 | 191 |
| In | ESSFdv | | 915 | 235 |
| No Data | ESSFdmw | moist | #N/A | #N/A |
| No Data | ESSFdmp | moist | #N/A | #N/A |
| No Data | ESSFdm | moist | #N/A | #N/A |
| No Data | ESSFdkw | moist | #N/A | #N/A |
| No Data | ESSFdcw | moist | #N/A | #N/A |
| Parkland | ESSFdcp | moist | 1,090 | 320 |
| In | ESSFdc | ■ | 833 | 316 |
| In | SBS un | dry | 624 | 236 |
| In | SBS dk | dry | 522 | 224 |
| In | SBPSxc | dry | 418 | 198 |
| In | SBPSmk | dry | 542 | 273 |
| In | SBPSmc | dry | 517 | 208 |
| In | SBPSdc | dry | 506 | 263 |
| In | PP xh | dry | 367 | 152 |
| In | PP dh | dry | 436 | 201 |
| In | MS xv | dry | 538 | 250 |
| In | MS xk | dry | 527 | 221 |
| In | MS dc | dry | 752 | 210 |
| In | IDF xw | dry | 351 | 174 |
| Pine < 10 % | IDF xm | dry | 396 | 215 |
| In | IDF xh | dry | 431 | 182 |
| In | IDF ww | dry | 998 | 216 |
| Pine < 10 % | IDF un | dry | 527 | 200 |

| | | | | |
|---|---|---|---|---|
| In | IDF mw | dry | 572 | 245 |
| In | IDF dw | dry | 652 | 183 |
| In | IDF dm | dry | 521 | 223 |
| In | IDF dk | dry | 470 | 212 |
| In | ICH xw | dry | 639 | 217 |
| In | BG xw | dry | 361 | 177 |
| In | BG xh | dry | 325 | 148 |
| Out Climate | AT un | not ranked | 1,587 | 521 |
| Out Climate | AT unp | not ranked | 1,408 | 487 |
| Out Climate | BWBSdk | not ranked | 501 | 248 |
| Out Climate | BWBSmw | not ranked | 506 | 325 |
| Out Climate | BWBSun | not ranked | 1,009 | 425 |
| Out Climate | BWBSvk | not ranked | 1,223 | 391 |
| Out Climate | BWBSwk | not ranked | 619 | 374 |
| Out Climate | CDF mm | not ranked | 1,089 | 200 |
| Out Climate | CWH dm | not ranked | 2,069 | 453 |
| Out Climate | CWH ds | not ranked | 1,588 | 329 |
| Out Climate | CWH mm | not ranked | 2,845 | 432 |
| Out Climate | CWH ms | not ranked | 2,133 | 462 |
| Out Climate | CWH un | not ranked | 1,081 | 215 |
| Out Climate | CWH vh | not ranked | 3,467 | 870 |
| Out Climate | CWH vm | not ranked | 3,603 | 785 |
| Out Climate | CWH wh | not ranked | 2,161 | 529 |
| Out Climate | CWH wm | not ranked | 2,237 | 643 |
| Out Climate | CWH ws | not ranked | 1,841 | 453 |
| Out Climate | CWH xm | not ranked | 1,906 | 332 |
| Out Climate | MH mm | not ranked | 3,132 | 714 |
| Out Climate | MH mmp | not ranked | #N/A | #N/A |
| Out Climate | MH un | not ranked | 2,214 | 649 |
| Out Climate | MH wh | not ranked | 4,138 | 1,053 |
| Out Climate | MH whp | not ranked | #N/A | #N/A |
| Out Climate | SWB dk | not ranked | 1,176 | 506 |
| Out Climate | SWB mk | not ranked | 665 | 387 |
| Out Climate | SWB mks | not ranked | #N/A | #N/A |
| Out Climate | SWB un | not ranked | 639 | 296 |
| Out Climate | SWB vk | not ranked | 1,638 | 564 |

| Formatting | Decision process |
|---|---|
| | Agreement between summer and annual precip rating |
| wet | Expert opinion |
| moist | |
| dry | |
| wet | Pine < 10% or parkland - Falls in group based on summer precip alone |
| moist | |
| dry | |
| | No climate data - rating based on similarity of subzones |
| not ranked | Climate out so ranking is irrelevant |

| Formatting | Decision process |
|---|---|
| | Agreement between summer and annual precip rating |
| ■<br>dry | Expert opinion |
| wet<br>moist<br>dry | Pine < 10% or parkland - Falls in group based on summer precip alone |
| wet<br>moist<br>dry | No climate data - rating based on similarity of subzones |
| not ranked | Climate out so ranking is irrelevant |

# Provincial Level Projection of the Current Mountain Pine Beetle Outbreak: An Overview of the Model (BCMPBv.2) and Results of Year 2 of the Project

## Appendix 5

## Results of a Reconnaissance Trip from Vanderhoof to the Kenney Dam; September 2004

*Supported by the*
*Mountain Pine Beetle Initiative of the Canadian Forest Service*
*and the BC Forest Service*

Canada

BRITISH
COLUMBIA

Marvin Eng, Research Branch, BC Forest Service

September 2004

## Introduction

On September 22, 2004 Nathan Voth (Stewardship Technician, Vanderhoof District) and I drove from Vanderhoof to Kenney Dam and back. Our intent was to get some indication as to how well the projection was matching with reality. The results are presented below. We made 6 stops and investigated 8 plots. We also hiked through the Kenney Dam fire and found very heavy levels of mortality in all the remaining pine.

## Observations at Plots

- Plot 1 53:46:25.3 124:21:9.1
  - 65 year old spaced natural stand. Very heavy attack in all stems above 12.5 cm (80 to 100% kill). Large larvae, some starting to pupate, indicating attack is the result of an early flight.
    - Projection underestimates kill. Pixels in the area range from <10 % kill to 50 to 80% kill
- Plot 2 53:33:47.8 124:35:15.2
  - 100% kill in pine above 12.5 cm dbh. Some small pine appear to have survived the MPB attack but no are attacked and killed by Ips.
    - Projection underestimates kill. Pixels in the area are in the 50-80% and 80 to 100% categories
- Plot 3 53:34:8.7 125:00:4.7
  - Approximately 20 year old spaced and pruned stand. 50% of stems (counted) killed by MPB. Blue stain present but no brood appears to have been produced.
    - Projection significantly under-estimates kill. This is a plantation. The trees are < 60 years old and therefore are not subject to kill in the model

- Plot 3a 53:34:8.7 125:00:4.7
  - mature stand ~100 years old with good spruce understory. Approximately 20 of the volume in the stand is spruce. 100% mortality in pine.
    - Projection underestimates kill. Pixels in the area are in the 50-80% and 80 to 100% categories
- Plot 4 53:33:2.3 125:03:5.75
  - Mature stand nearly pure pine. All stems above 12.5 cm dbh are killed. The "green" stems in the photo are all green attack and dead.
  - Projection underestimates kill. Pixels in the area are in the 50-80% and 80 to 100% categories
- Plot 5 53:40:15.8 124:56:59.8
  - Mixed pine – spruce (50% 50%) stand. 1 live pine tree found. Lots of spruce blowdown
    - Projection underestimates kill to some extent. Pixels in the area are in the 50-80% and 80 to 100% categories
- Plot 6 53:43::09.7 124:57:19.8
  - pure pine with a good pine understory. 80-100 years old. Recent kill with some green attack. ~80 of all stems in the canopy have been killed.
    - Projection significantly under-estimates kill. Pixels in the area are predominantly in the 11-25% kill category
- Plot 6a 53:43::09.7 124:57:19.8
  - 80 – 100 year old stand of pure pine with a poorly developed understory. 3 prisms sweeps (5 BAF) counted 22 trees larger than 12.5 cm dbh. 81% killed (71% red and dead, 10% green attack).
    - Projection significantly under-estimates kill. Pixels in the area are predominantly in the 11-25% kill category

## Summary

Mortality at or near 100% of merchantable volume was observed in all mature plots south of the "Holy Cross Mountain salvage line" (plots 2, 3a, 4 and 5).

Mortality levels above 80% of merchantable volume were observed in mature (plots 6 and 6a) and a 65 year old plot (plot 1) north of the "Holy Cross Mountain salvage line".

Mortality levels in 20 year old spaced and pruned stands (plot 3) are not expected in the model.

Plot 1 53:46:25.3 124:21:9.1

65 year old spaced natural stand. Very heavy attack in all stems above 12.5 cm. Large larvae, some starting to pupate, indicating attack is the result of an early flight.

Plot 1 showing early faders

Plot 2

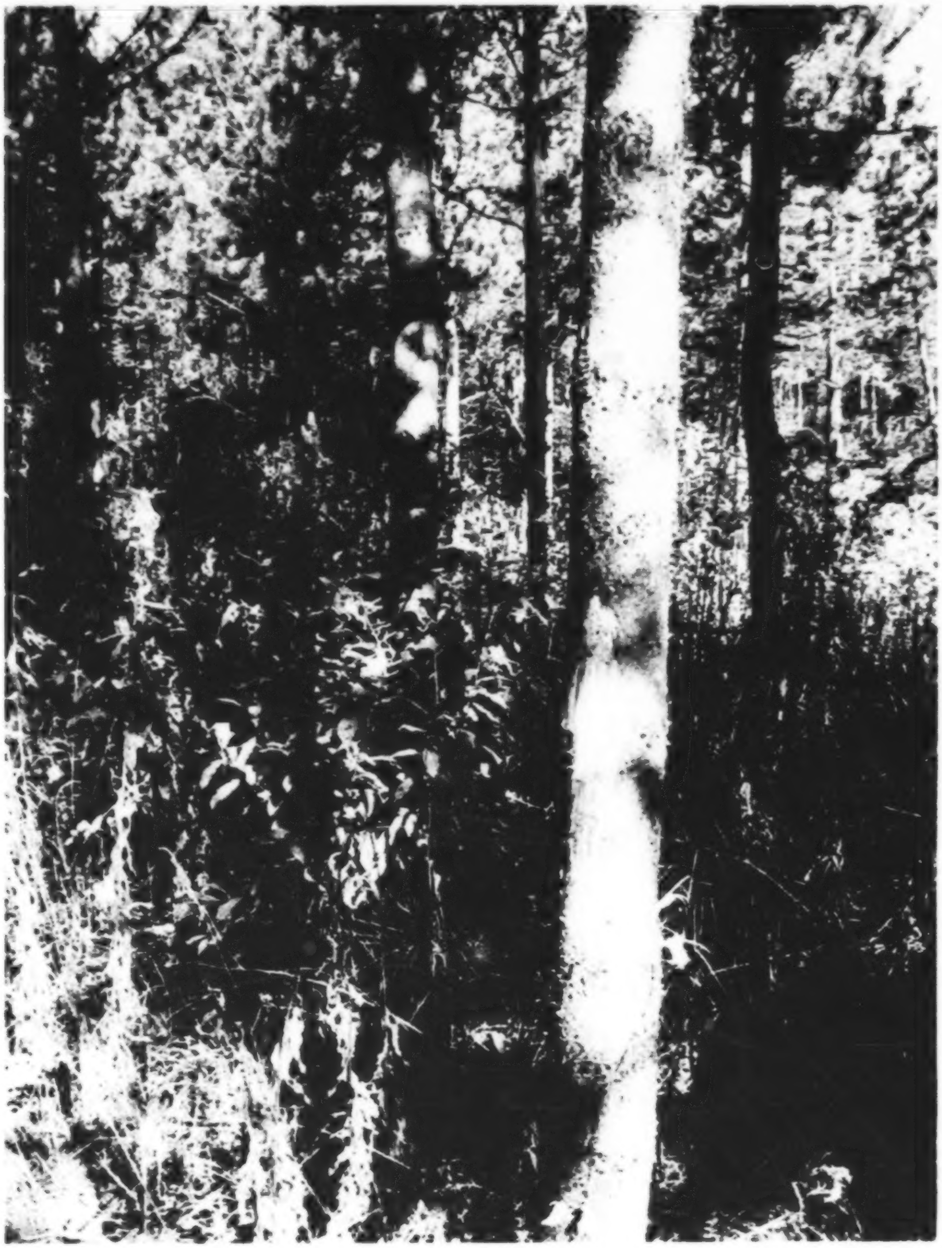
53:33:47.8 124:35:15.2

100% kill in pine above 12.5 cm dbh. Some small pine appear to have survived the MPB attack but no are attacked and killed by Ips.

Plot 3

53:34:8.7 125:00:4.7

Approximately 20 year old spaced and pruned stand. 50% of stems (counted) killed by MPB. Blue stain present but no brood appears to have been produced.



Plot 3a

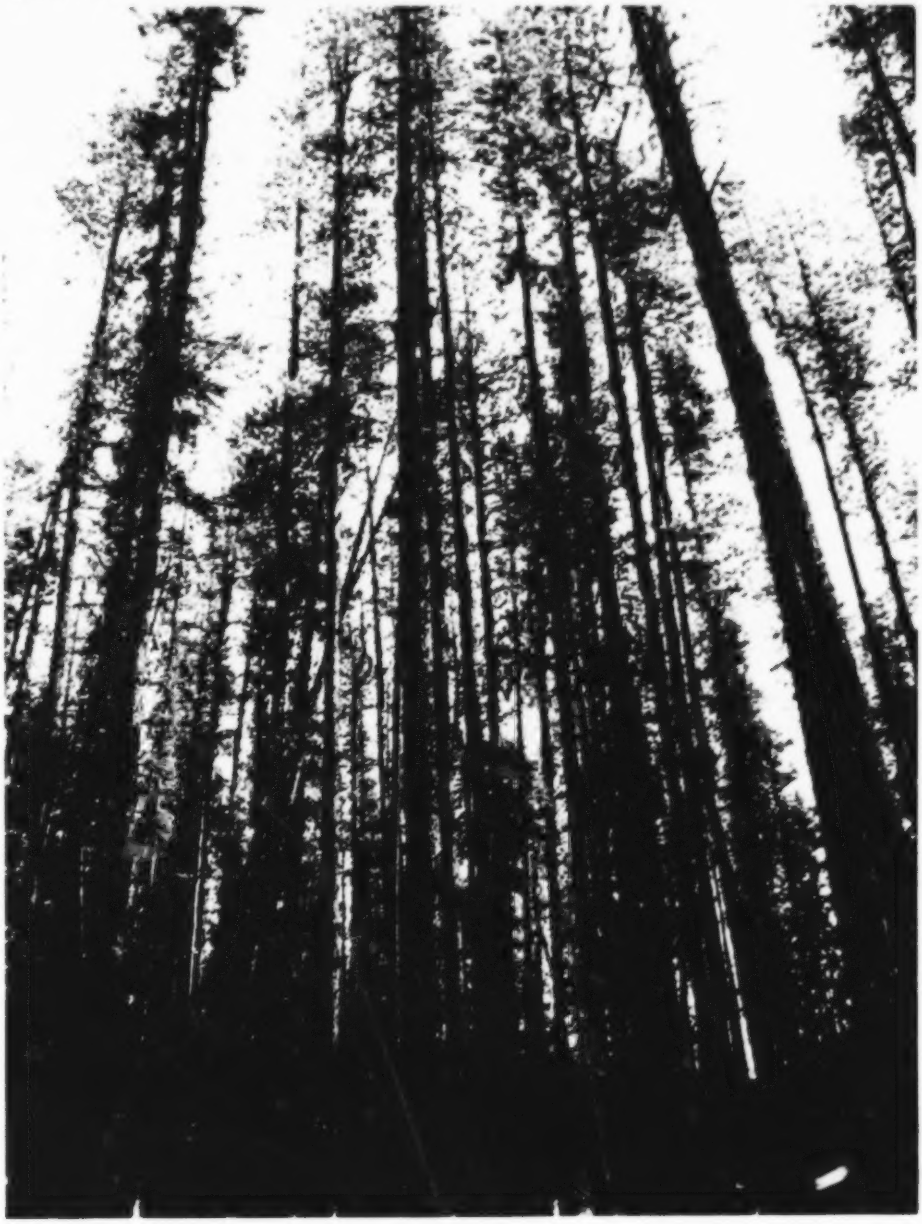
53:34:8.7 125:00:4.7

mature stand ~100 years old with good spruce understory. Approximately 20 of the volume in the stand is spruce. 100% mortality in pine.

Plot 4

| | |
|---|---|
| 53:33:2.3 | 125:03:5.75 |

Mature stand nearly pure pine. All stems above 12.5 cm dbh are killed. The "green" stems in the photo are all green attack and dead



Plot 4

Plot 5

53:40:15.8    124:56:59.8

Mixed pine – spruce (50% 50%) stand. 1 live pine tree found. Lots of spruce blowdown

Plot 6

53:43::09.7 124:57:19.8

pure pine with a good pine understory. 80-100 years old. Recent kill with some green attack. ~80 of all stems in the canopy have been killed.

Plot 6a

53:43::09.7    124:57:19.8

80 – 100 year old stand of pure pine with a poorly developed understory. 3 prisms sweeps (5 BAF) counted 22 trees larger than 12.5 cm dbh. 81% killed (71% red and dead, 10% green attack).